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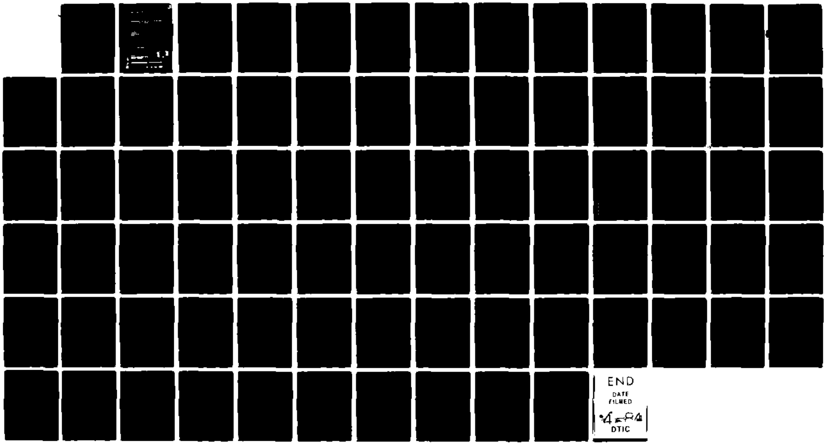

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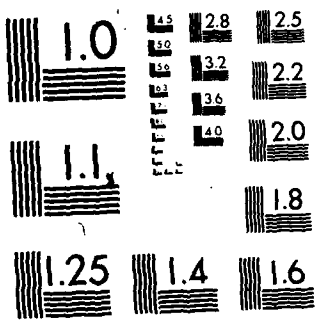

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ENVIRONMENTAL CONTROL SYSTEM CONCEPT STUDY FOR A TYPE A V/STOL AIRCRAFT

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Energy-efficient closed-loop air and vapor cycles, rotary-vaned positive-displacement air cycle machinery, partial closed-loop air cycles (Shoestring Systems) and advanced centrifugal machinery with high-speed electric motor drives show promise for advancing the state-of-the-art in ECS design. This report presents study results to identify the benefits of this advanced ECS technology when applied to subsonic Navy V/STOL aircraft. Results show that the use of bleed air driven turbo-machines with partial recirculation of used cooling air back to the turbomachinery (Shoestring System) leads to the lowest overall system takeoff gross weight penalty to the aircraft and to the lowest life cycle costs. For this system, the total life cycle cost penalty decreased with decreasing avionic junction temperatures between 115 and 80°C, and then increased rapidly at junction temperatures lower than 80°C.

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PREFACE

In the preparation of this report, the authors have had to call in the expertise of many other Grummanites. We would therefore like to specifically thank the following for their valuable contributions:

W. Reis	-	ECS
V. Cirrito	-	Thermodynamics
B. Steinberg	-	R&M
R. Thompson	-	Propulsion
W. Zukoski	-	Weights
B. Borgeson	-	LCC
R. Penner	-	LCC
S. Iwanski	-	LCC
J. Conover	-	Secondary Power
E. Ramirez	-	Avionics

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1 - STUDY OVERVIEW AND SUMMARY

1.1 BACKGROUND

The Environmental Control Systems (ECS) on existing aircraft are not significantly more advanced than the original open-loop air-cycle ECS developed for early turbine-powered aircraft. These systems were quite adequate for the earlier aircraft, because the penalty of extracting engine bleed air was not critical to the mission. In addition, the avionics systems heat loads were small, with limited temperature sensitivity so that ambient cooling was sufficient. On later aircraft, the impact on the vehicle became significant since the engines became more sensitive to the extraction of bleed air, resulting in reduced aircraft performance. Compounding this effect were the increased demands of the avionics equipment whose requirements for cooling became more complex, more critical and greater. For V/STOL aircraft, with their high sensitivity to engine bleed air extraction, this ECS growth trend must be reversed.

ECS progress is required for additional reasons. Advanced technology engines are sensitive to engine bleed-air extraction, and the latest avionics require better quality cooling and tighter temperature control. Operation from smaller ships with limited aircraft and maintenance capabilities requires greater system and avionics reliability and reduced shipboard maintenance. In addition, the systems must be self-sufficient and free from the need for ground support equipment for their operation and checkout.

Recent industry and government studies and exploratory work show considerable promise for advancing the state of the ECS art. Specific areas include:

- Energy-efficient closed loop air and vapor cycles
- Advanced rotary-vaned positive-displacement air cycle machinery
- Advanced centrifugal machinery
- Variable speed high-speed electric motors.

These areas should serve as the basis for the development of advanced ECS concepts capable of meeting the severe aircraft and ECS requirements imposed by V/STOL vehicles. In recognition of this, the Navy placed Grumman under contract (Ref 1) to study light-weight ECS concepts for application to V/STOL aircraft and thereby establish the specific technology developments required for future V/STOL aircraft. Grumman, with the cooperative efforts of various ECS equipment manufacturers,* examined numerous advanced ECS concepts as applied to a specific V/STOL aircraft design. The evaluations of these was performed on the basis of overall penalty to the vehicle and total life cycle cost.

1.2 STUDY APPROACH

The ultimate goal of this effort was to identify the technology required for future V/STOL aircraft ECS development. This goal resulted in the requirement for this study to better specify and justify technology developments necessary to achieve this. To satisfy this study requirement, various ECS concepts were synthesized and evaluated using a subsonic V/STOL aircraft with an AEW mission as a design base. Rationale used for ECS evaluation are aircraft take-off gross weight (TOGW) and life cycle costs (LCC). The costs consider not only ECS costs but the impact of the ECS on avionics life cycle costs and on aircraft operating costs. Selection of the most promising ECS concepts on this basis resulted in the identification of technology development areas that have the most impact on vehicle cost effectiveness. Towards this end a two step effort was conducted. The first step was a preliminary system concept synthesis and evaluation effort which resulted in a number of well-defined ECS system concepts and well-defined penalties (e.g., weight, power, etc.) in terms of TOGW. Upon completion of this step a screening of concepts was performed to reduce the number of concepts to those which on the basis of both minimum TOGW penalty (to the aircraft) and sound engineering judgement were most likely to attain the highest scores during the

*These manufacturers included AiResearch Mfg Division of Garrett Corp, Los Angeles, CA; Hamilton Standard Division of United Aircraft, Windsor Locks, CT; and Sundstrand Aviation Mechanical Division of the Sundstrand Corp, Rockford, IL.

next step. During the second step, the surviving system concepts were re-examined under the impact of additional design considerations, e.g., reliability, self-sufficiency, cost, etc., and then evaluated on a life cycle cost basis. Included in the life cycle cost evaluation were the impact of the ECS on:

- Avionics operating costs which are interrelated to the ECS through the mechanism of avionic junction temperatures
- Airframe operational costs which are interrelated to the ECS through ECS system weight and power extraction penalties.

The final evaluation of ECS system concepts(s) was performed on a weapons system cost effectiveness basis.

1.3 SUMMARY OF CONCLUSIONS

The major results of the study for a subsonic V/STOL aircraft show that the use of bleed air driven turbo-machines and partial recirculation of used cooling air back to the turbo- machinery (for reconditioning) leads to the lowest overall system penalty to the aircraft. On a life cycle cost basis such a system concept also results in the lowest costs. As opposed to this partially closed ECS concept, it was found that shaft-driven closed-loop ECS concepts, whether employing a vapor cycle unit or an air cycle unit, resulted in both the highest overall system penalty to the aircraft and the largest LCCs. It was further discovered that whereas the TOGW penalty increases with decreasing avionic junction temperatures for all ECS concepts investigated, only for the closed loop concepts do the LCCs behave this way. For the remaining systems the LCCs actually bottomed out in the 80°C to 90°C temperature range, suggesting that an 80°C to 90°C junction temperature is a practical lower design limit.

1.4 SUMMARY OF RECOMMENDATIONS

Because the study results are affected to a great degree by aircraft mission profile and aircraft design, it is recommended that the existing study be extended to:

- Include several partially closed ECS concepts. For example, a recirculating bootstrap air cycle or a recirculating three-wheel air cycle could serve as the nucleus of a partially closed ECS. In this manner the optimum system concept could be identified

- Determine the LCC and the aircraft penalties associated with different ratios of WRA to rack-mounted avionics. Since this ratio affects the sizing of the ECS and thus its penalties, it is suggested that it be made a study variable so that the optimum mix can be determined for subsonic V/STOL aircraft.

In addition to the above study extensions it is recommended that a study similar to the one just conducted be done for a supersonic fighter V/STOL aircraft. In this way all the AEW/ASW and fighter aircraft V/STOL concepts will be covered.

2 - STUDY GUIDELINES

2.1 AIRCRAFT AND MISSION MODEL

A representative Grumman-designed subsonic V/STOL aircraft designed for an AEW mission was selected for the study (Fig. 1, Ref 2). The aircraft is a high wing vehicle with one high bypass ratio turbofan lift/cruise engine mounted on each wing. Cross shafting interconnects the two fans through gearboxes.

The aircraft is capable of vertical and short field takeoffs from a variety of ships and sites either having or not having ground support equipment. An Auxiliary Power Unit provides the services (i.e., air, electrical power, or shaft power, etc.) required for aircraft support when GSE is not available.

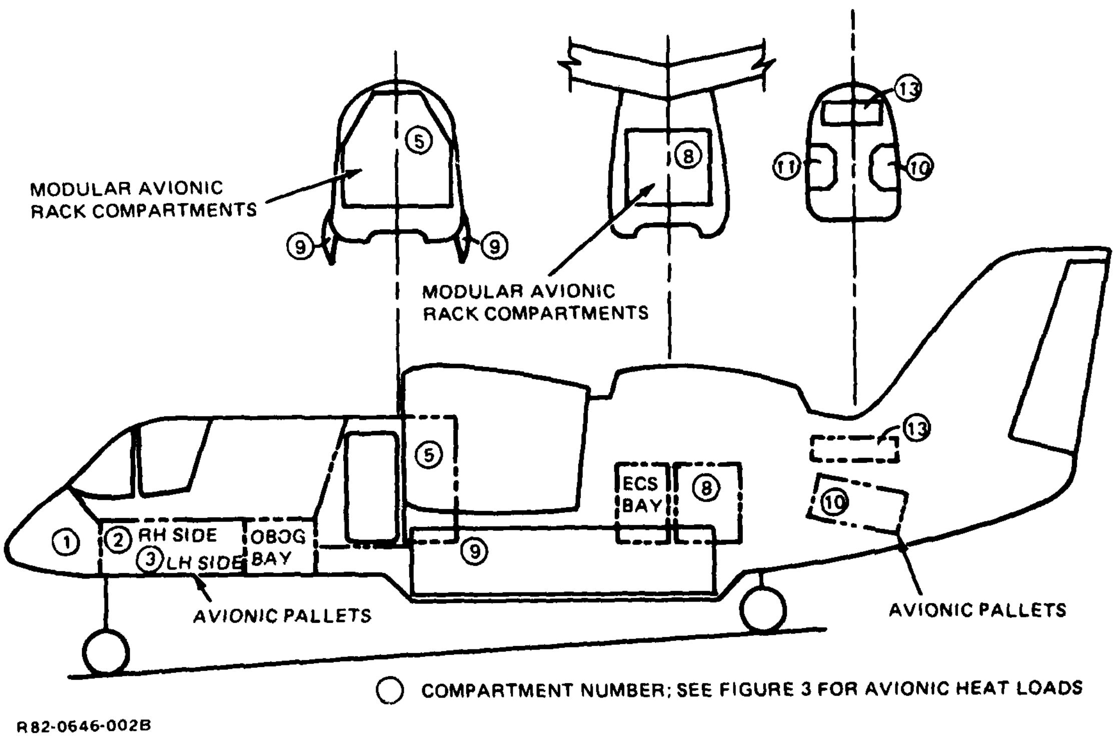

Figure 1. AEW V/STOL Inboard Profile

The mission selected for systems evaluation consists primarily of high altitude cruise-out, loiter and cruise-back mission segments typical of AEW operation and is shown in Table 1.

Table 1 Mission Model (Standard Day)

MISSION SEGMENT	ALTITUDE, FT X 10^3	MACH NO.	TIME, MIN	DISTANCE, N MI
WARM-UP	0	0	2.8	0
CLIMB	0-37	0.69	2.9	18.4
CRUISE-OUT	38	0.59	23.4	131.6
LOITER	37	0.50	180.0	–
CRUISE BACK	45	0.65	24.3	150.0
RESERVES	–	–	10.0	–

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2.2 AVIONICS SYSTEM DESCRIPTION

The aircraft avionics consist of ambient-air cooled equipment and rack-mounted force-cooled equipment, as described below.

2.2.1 Avionics System Partitioning

The avionics system configured for this AEW V/STOL aircraft results in a 30 KW heat load. Of this load approximately 13 KW was in ambient air cooled Weapon Replaceable Assembly (WRA) enclosures (identical to those used in current aircraft), and the remainder in eight modular avionic racks. The antenna power modules were included in this latter group. The racks each had the construction shown in Fig. 2 and require forced cooling.

Aside from the WRAs located in the cockpit, all other WRAs and the racks are located in unpressurized compartments. Referring to Fig. 1, the aircraft inboard profile, the racks are located in compartments numbers 5 and 8 while the WRAs are located in the remaining compartments. The compartment avionics heat load corresponding to this distribution is given in Table 2.

2.2.2 Integrated Avionic Racks

The racks, previously shown in Fig. 2, are made up of ISEM 2A cards which are cooled internally with recirculating air. Each rack has its own air recirculation system which is located within the rack's enclosure. The enclosure, although unpressurized, is tight enough to eliminate recirculation air leakage. The recirculation air is cooled in a heat exchanger, which is inter-

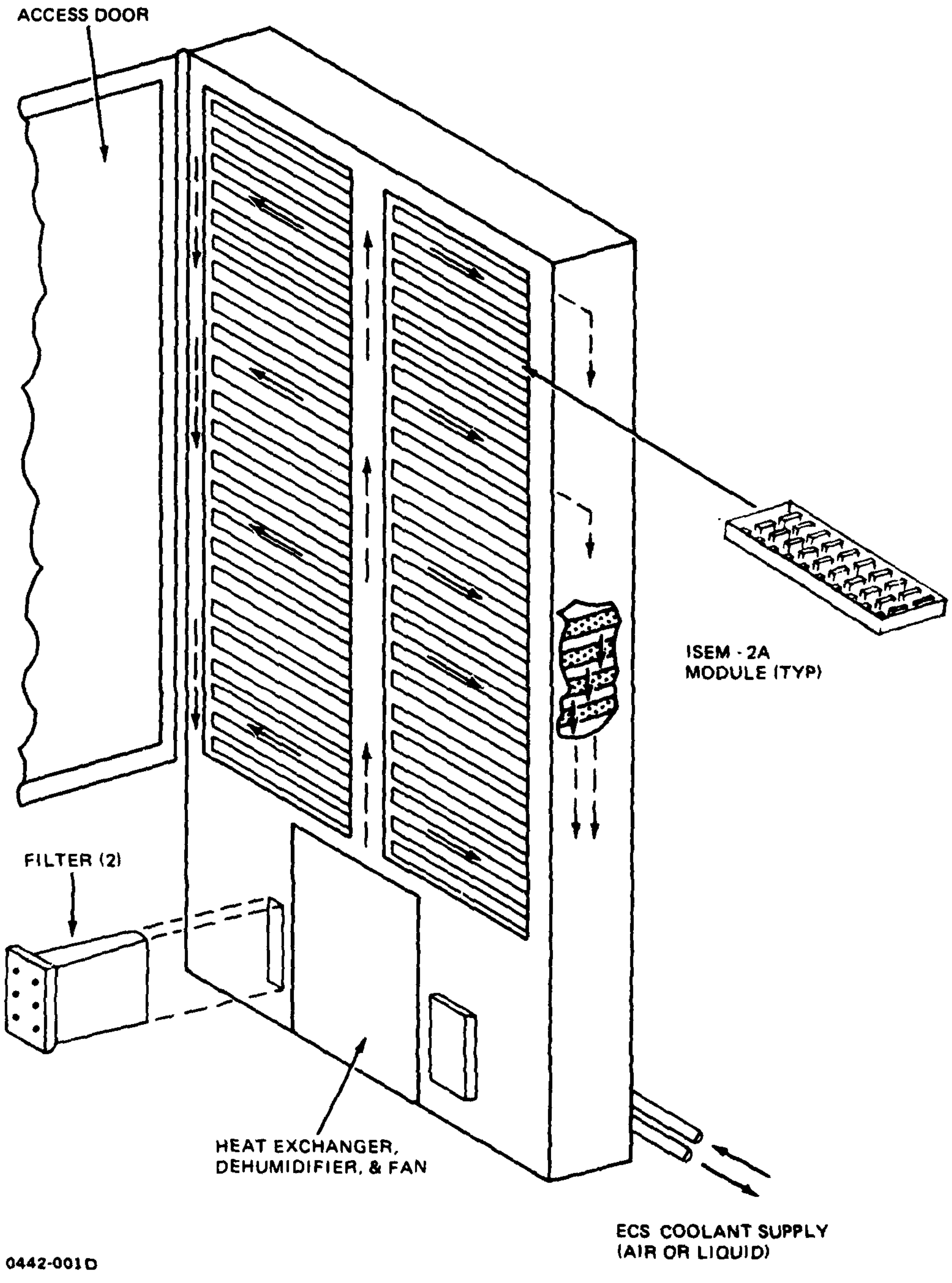

Figure 2. Typical Modular Avionic Rack

Table 2 Compartment Avionic Heat Loads

COMPARTMENT NUMBER	AVIONIC HEAT LOAD (WATTS)
1	760
2	95
3	95
5	13070 (IN RACKS)
8	3580 (IN RACKS)
9	3000 (ANTENNA POWER MODULES)
10	800
11	800
12	3000 (ANTENNA POWER MODULES)
13	1240
COCKPIT	3600

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nal to the rack, before being circulated over the ISEM 2A modules, and then returned to the heat exchanger. The heat exchanger interfaces with the ECS coolant which, depending upon the ECS, may be a liquid or gas. The recirculation air flow requirements for the rack modules depend upon the recirculation air temperature and the average component junction temperature on the module. For the 20 watts per module assumed for each ISEM 2A module, the flow requirements per kilowatt of rack heat load are given in Fig. 3.

2.2.3 WRAs

All weapons replaceable assemblies regardless of location were assumed to be ambient air cooled via natural convection. For those WRAs located in unpressurized compartments, Fig. 4 shows the required compartment ambient temperature in order to achieve a specific average component junction temperature. These curves are the unpressurized compartment temperature-altitude schedules necessary for maintaining fixed WRA average component junction temperature. Similar temperature-altitude sch[illegible] for the cockpit do not exist since human factor considerations dict[illegible] [illegible]quired cockpit ambient temperatures and pressures. Consequently, [illegible] n the cockpit were not examined in terms of component junction [illegible]ure. However, since cockpit temperature and pressure variations are sma[illegible] compared to the unpressurized compartment variations, no significant component temperature excursions occur under normal circumstances.

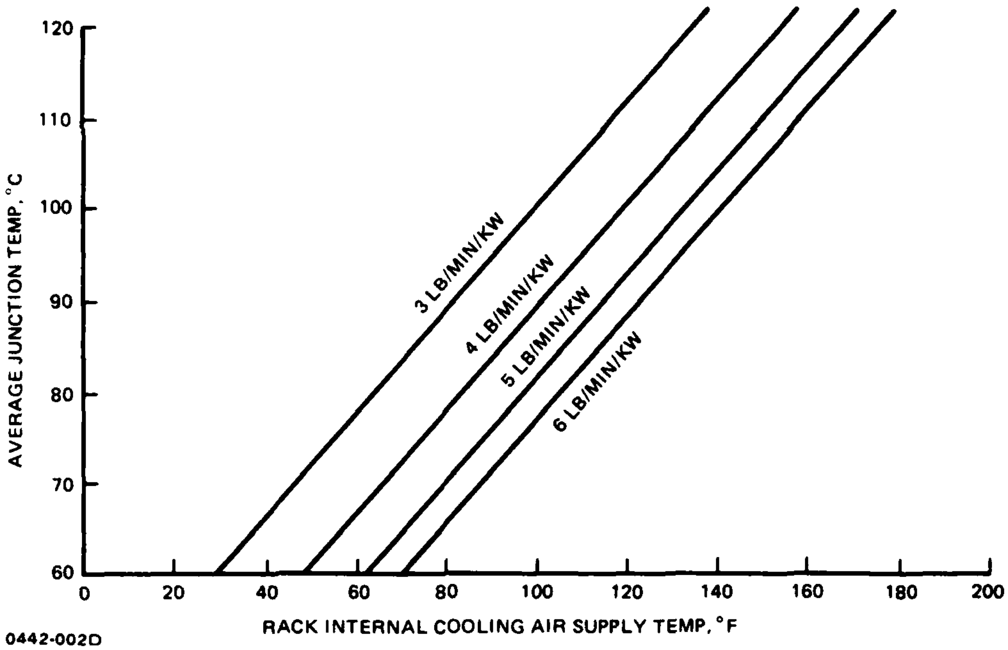


Figure 3. Avionic Rack Internal Cooling Air Flow Requirements

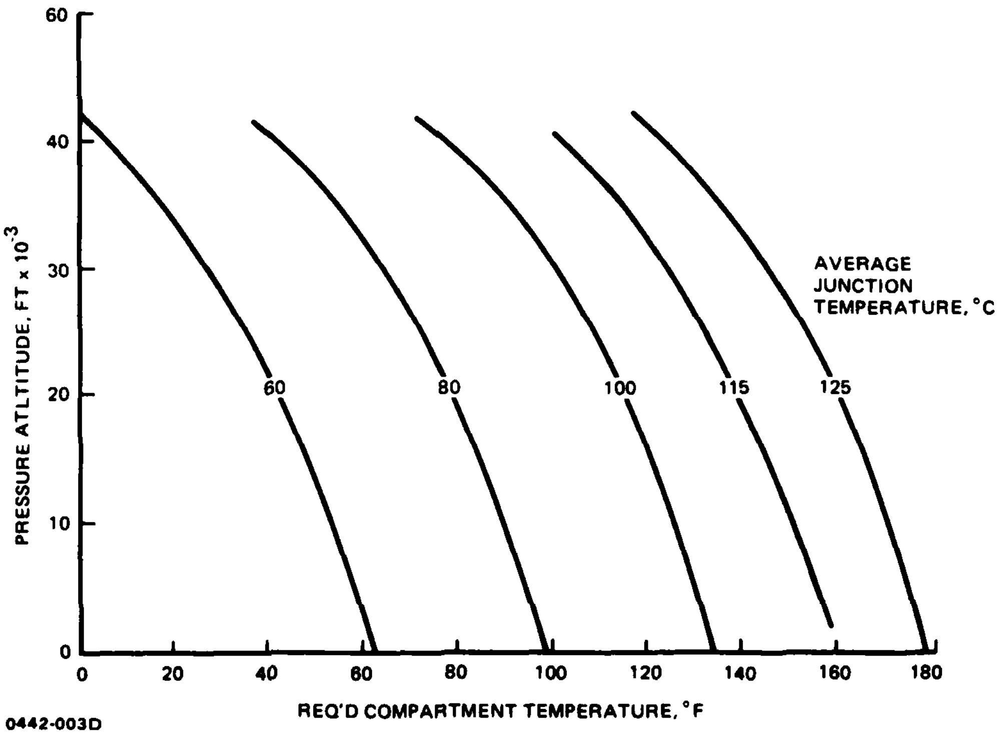


Figure 4. WRA Compartment Average Required Temperatures

2.3 ECS DESIGN REQUIREMENTS

The U.S. Navy ECS design specification, MIL-E-18927D, was used to furnish system design criteria, while MIL-STD-210A provided both the hot and cold day atmospheric temperature data necessary for system component sizing.

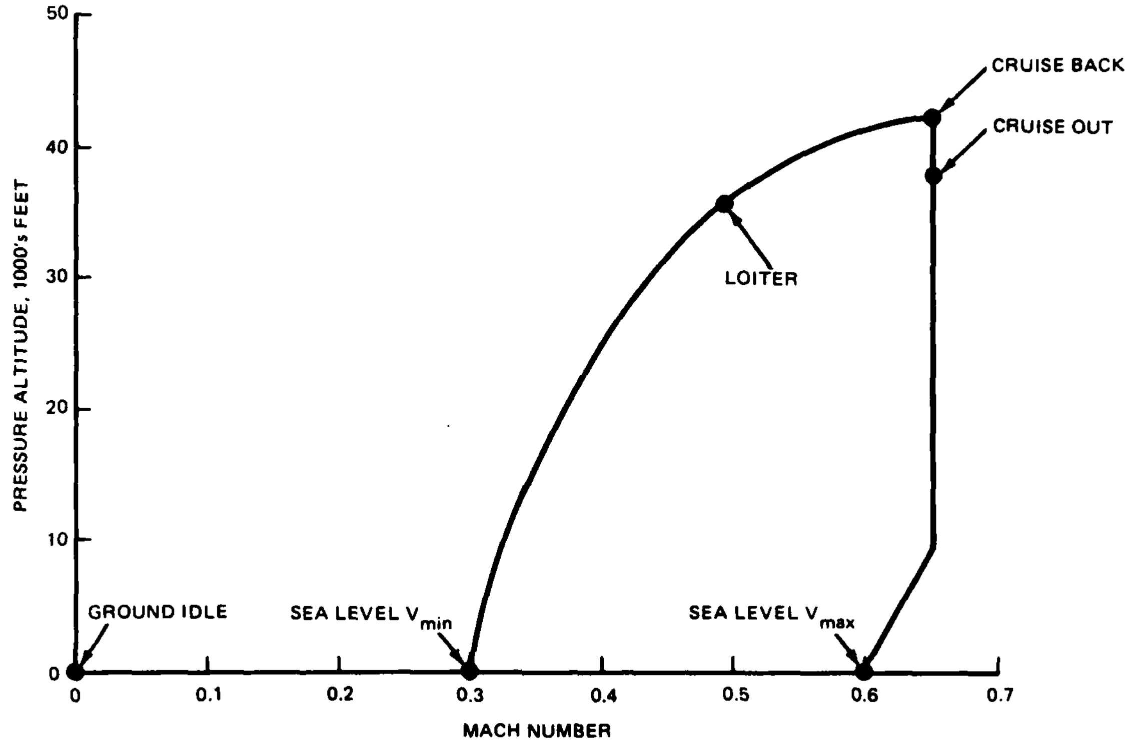
The ECS, sized and configured to satisfy all requirements for steady state hot and cold day operation over the aircraft flight envelope shown in Fig. 5, satisfies the following four basic functions:

1) Cockpit air conditioning and pressurization requirements are satisfied by providing sufficient cabin air flow at the proper temperature and pressure to maintain the cockpit temperature between 60° and 80°F and the pressure equal to: ambient pressure at aircraft altitudes between 0 and 5,000 feet, a 5,000 feet cabin altitude between 5,000 and 35,000 feet, 8.8 psi above ambient pressure at aircraft altitudes of 35,000 feet and above. A 3.5 lb/min. production cockpit air leakage rate (with a 5.6 lb/min. service leakage rate) and a minimum of 48 cfm for crew ventilation are provided for also.

2) Vehicle anti-icing, de-icing, defogging and defrosting is accomplished in sundry ways, and the method is different for each of the four vehicle areas considered. The front windshield utilizes electrical heaters for anti-icing and defog while the cockpit canopy side panels utilize conditioned bleed air at 220°F to accomplish the same functions. Conditioned bleed air is also utilized for the engine inlets while deicing of the empennage is done with pneumatic boots. Rain removal is accomplished with windshield wipers.

3) Oxygen for the crew is provided by two on-board oxygen generating (OBOG) units each of which is sufficient for two persons. Bleed air flows of 70 lb. per hour (total) at temperatures between 40°F and 100°F and at pressures in the range of 25 to 125 psig are required for the OBOGs to produce the crew's oxygen.

4) Equipment and associated compartment cooling requirements are satisfied by providing sufficient coolant flow (air or liquid) flow at the proper temperature directly to the equipment in some cases and directly to the



DESCRIPTION	BLEED PRESS psia	BLEED AIR TEMP, °R (HOT DAY)	BLEED AIR TEMP, °R (STD DAY)
GROUND IDLE	95	1080	1005
SEA LEVEL V_{min}	130	1140	1060
SEA LEVEL V_{max}	380	1452	1370
LOITER	70	1120	1030
CRUISE BACK	70	1140	N/A
CRUISE OUT	80	1200	N/A

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Figure 5. AEW Mission Envelope and Engine Bleed Air Characteristics

equipment compartment in others. The electronic equipment and their associated compartment requirements were previously discussed in Section 2.2.

2.4 STUDY GROUND RULES

- Self-sufficiency - It was assumed that the avionics would be operated on a ship both on the flight deck and in the hangar. This means that the power and cooling required for the avionics on the flight deck would be provided via the main engine or an APU. For hangar operation, since neither the engine or the APU can be operated, it was assumed that ship's power, compressed air, or hydraulic power is used.
- Aircraft Electrical Power - a 270 Volt DC aircraft system was assumed.
- ECS Design Atmosphere - MIL-STD-210A hot and cold day atmospheres were used as the ECS design atmospheres. The U.S. standard atmosphere was used for the ECS penalty evaluation on aircraft TOGW.
- Avionics Cooling - All avionics were assumed to be either WRAs or racks. WRAs were treated as ambient cooled items; racks were forced cooled. The antenna power modules which were actually forced cooled WRAs were treated as racks (i.e., as having the same flow requirements as racks) for study purposes.

3 - ECS SUBSYSTEM PENALTY INVESTIGATIONS

3.1 PRELIMINARY SUBSYSTEM INVESTIGATIONS AND RESULTS

The preliminary investigations referred to in this section were the first step (see Section 1.2) of the study and consisted of the synthesis of a number of ECS concepts and their evaluation in terms of aircraft TOGW penalties only. To expedite this phase of the study certain simplifying assumptions were made to enable a more rapid sizing and evaluation to the ECS to take place. These are discussed below along with a discussion of the systems investigated and the study results.

3.1.1 Simplifying Assumptions

The key simplifying assumptions made during the ECS concept synthesis and sizing efforts were:

- The WRAs in the unpressurized compartments require no special cooling air, and are cooled either with cockpit discharge air or ram air. WRA compartment ambient temperature requirements are per MIL-E-5400 Class II and therefore no junction temperature control is required.
- The antenna power modules are assumed to be cooled just like the rack mounted avionics, and both will be supplied with 3 lbs per min. per Kw of airflow internally.
- Component junction temperatures for each rack mounted avionic and antenna power modules are to be maintained at + 85°C.

The remaining data used for the ECS design analysis are as previously discussed in section 2.0. To expedite the evaluation of the ECS concepts synthesized, the TOGW penalties provided in Table 3 were used.

The weight penalties are given for the vehicle and also for the three ECS requirements; engine bleed air, shaft power extraction and ram air. The first two columns list the mission segment and the percent of the total fuel that is expended on each segment. The next column shows that a constant vehicle weight penalty of 4 lb per lb of ECS hardware is assessed once for the entire mission. The next three columns present the penalties for fuel and associated weight that are assessed for each mission segment. For example, taking the

Table 3 Subsonic V/STOL-TOGW Penalties AEW Mission

MISSION SEGMENT	% TOTAL MISSION FUEL	VEHICLE WEIGHT lb/lb	ENGINE BLEED lb/lb/min	SHAFT POWER lb/HP	RAM AIR lb/lb/min
TAKE-OFF	7	4.0	2.94	0.123	NEGLIGIBLE
IRT CLIMB	12		0.76	0.264	0.12
CRUISE OUT & BACK	14		1.90	0.410	0.11
LOITER AT ALTITUDE ON STATION	54		12.0	2.20	0.42
S.L. LOITER	13		1.63	0.54	0.07

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bottom row of the figure, during sea level loiter which uses 13% of the total mission fuel, 1.63 lb of fuel and associated weight must be provided for each lb/min of air that is bled off the engine, 0.54 lb of fuel and associated weight must be provided for each HP extracted via a shaft and 0.07 lb of fuel and associated weight must be provided for each lb/min of ram air flowing into the ECS.

3.1.2 ECS Concepts Investigated

Twelve ECS concepts were synthesized and evaluated during the first phase of the study effort. The systems evaluated ranged from open loop to closed loop systems and included the following:

- Air cycle systems ranging from simple and bootstrap systems to shoe-string systems
- Single vapor cycle systems to a combination air cycle-vapor cycle system
- Positive displacement closed loop air cycle systems alone and in combination with a simple air cycle.

The system schematics, weight breakdowns, and system performance (over the aircraft mission profile) are given in detail in Appendix A while the results of the evaluation of each on a TOGW basis are shown in Table 4 On the basis of these results the shoestring air cycle, single vapor cycle, single positive displacement and single centrifugal closed loop air cycle system were selected for further investigation during the second phase of the study effort. Selection of the positive displacement and centrifugal closed loop air cycle concepts for further study were done primarily on the basis that a closed loop air cycle represents a technology advance and thus warrants much

Table 4 ECS Evaluation

CONCEPT	TOGW PENALTY (LBS)
• BLEED AIR DRIVEN ECS	
SIMPLE AIR CYCLE	3274
BOOTSTRAP	3756
THREE WHEEL	3677
SHOESTRING	3257
• SHAFT DRIVEN ECS	
SINGLE VAPOR CYCLE	3372
• HYBRID ECS	
SIMPLE A/C + VAPOR CYCLE (LIQ DIST)	3537
SIMPLE A/C + VAPOR CYCLE (AIR DIST)	3602
SIMPLE A/C + POSITIVE DISPL.	3745
• SHAFT DRIVEN ECS FOR RACK ONLY	
SINGLE VAPOR CYCLE	1420
SINGLE POSITIVE DISPLACEMENT	
CLOSED LOOP	1565
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closer study. A single bootstrap air cycle system was also selected to serve as a baseline for the study effort.

3.1.3 Supplemental Investigations

During the ECS design analysis effort described above sundry supplemental investigations were conducted. An example of this was a feasibility study of fuel versus ram air as a heat sink. An investigation of the fuel temperatures available versus those of ram air under the three major flight conditions of interest showed conclusively that both during extreme hot day (per MIL STD 210A) and standard day flights (per U.S. Standard Atmosphere of 1962) the fuel temperature available was almost always significantly higher than the ram air temperatures available. This is shown below in Table 5. On this basis it was concluded that fuel would not be a practical heat sink. Thus, it was not reflected in any of the system concepts synthesized, and ram air was used exclusively.

Table 5 Fuel Heat Sink Study Results

- SINK TEMPERATURES (°F)

CONDITION	HOT DAY		STD DAY	
	FUEL	AIR	FUEL	AIR
S. L. STATIC	125	103	100	60
S. L., V_{MAX}	135	143	110	96
35K, LOITER	100	-5	60	-47

- CONCLUSION

FUEL IS NOT A PRACTICAL HEAT SINK SINCE RAM AIR IS AVAILABLE AT A MUCH LOWER TEMPERATURE

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Another supplemental study was the evaluation of air and liquid heat transport loops for cooling the modular avionic racks. The study, which was performed with a vapor cycle unit as the ultimate heat sink, showed that the TOGW penalty associated with an air heat transport loop is larger primarily because of the large power penalties due to the fans and the increased system weight. Because of this finding only liquid heat transport loops were considered during the second study phase.

3.2 FINAL SUBSYSTEM INVESTIGATION AND RESULTS

3.2.1 Description, Performance and Penalties

The five subsystems studies in detail during the second phase of the study fall into three major categories, (Fig. 6) are:

• Open loop ECS	- Bootstrap air cycle ECS
• Partially closed loop ECS	- Shoestring air cycle ECS
• Fully closed loop ECS	- Vapor cycle ECS
	- Electrically driven centrifugal closed loop air cycle ECS
	- Hydraulically driven positive displacement closed loop air cycle ECS.

Each of these were studied at three avionic junction temperatures, i.e., 60°C, 80°C and 115°C.

3.2.1.1 **Bootstrap Air Cycle ECS** - This bleed air driven ECS is comprised of three major subsystems, as shown in Fig. 7, namely: the heating and ventilation, air distribution, and air cycle subsystems.

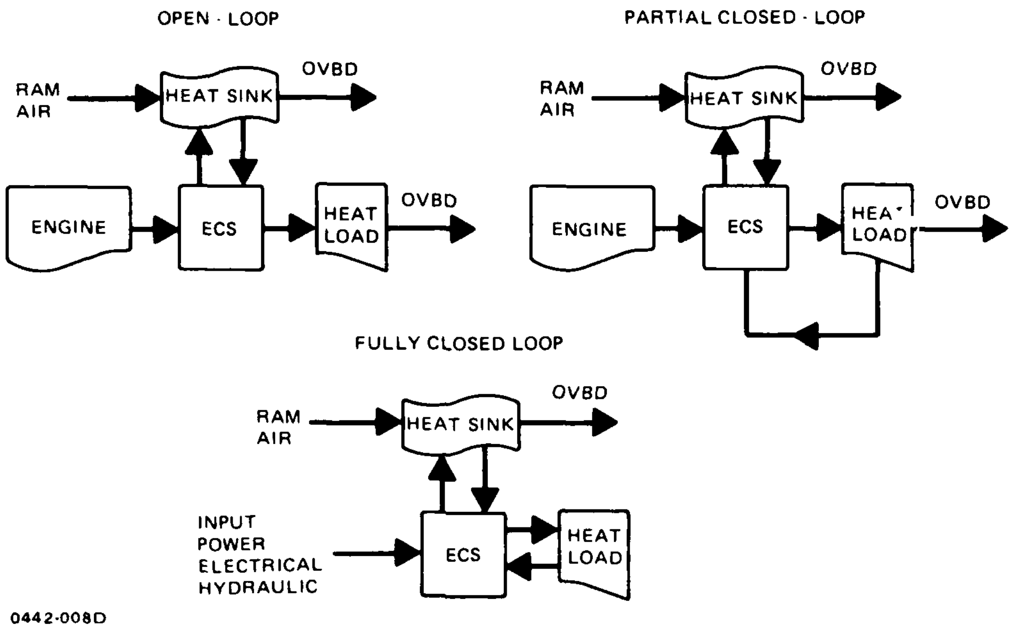

Figure 6 Basic ECS Categories

Heating & Ventilation Subsystem – This subsystem consists primarily of control valves and plumbing. It provides temperature controlled bleed air to both the cockpit and the WRA compartments to satisfy their ventilation and/or heating requirements.

The heating and ventilation subsystem effectively processes bleed air to the 250°F temperature level, for compartment temperature control purposes (and 200°F for aircraft services) and modulates the quantity supplied to each. This is accomplished by drawing primary air supply from the air cycle subsystem at a point where the temperatures are slightly below 200°F, and metering quantities of raw bleed via temperature control valves in appropriate amounts to adjust mixture temperatures to 250°F for the WRA compartments and to 200°F for the remaining aircraft services (e.g., defog).

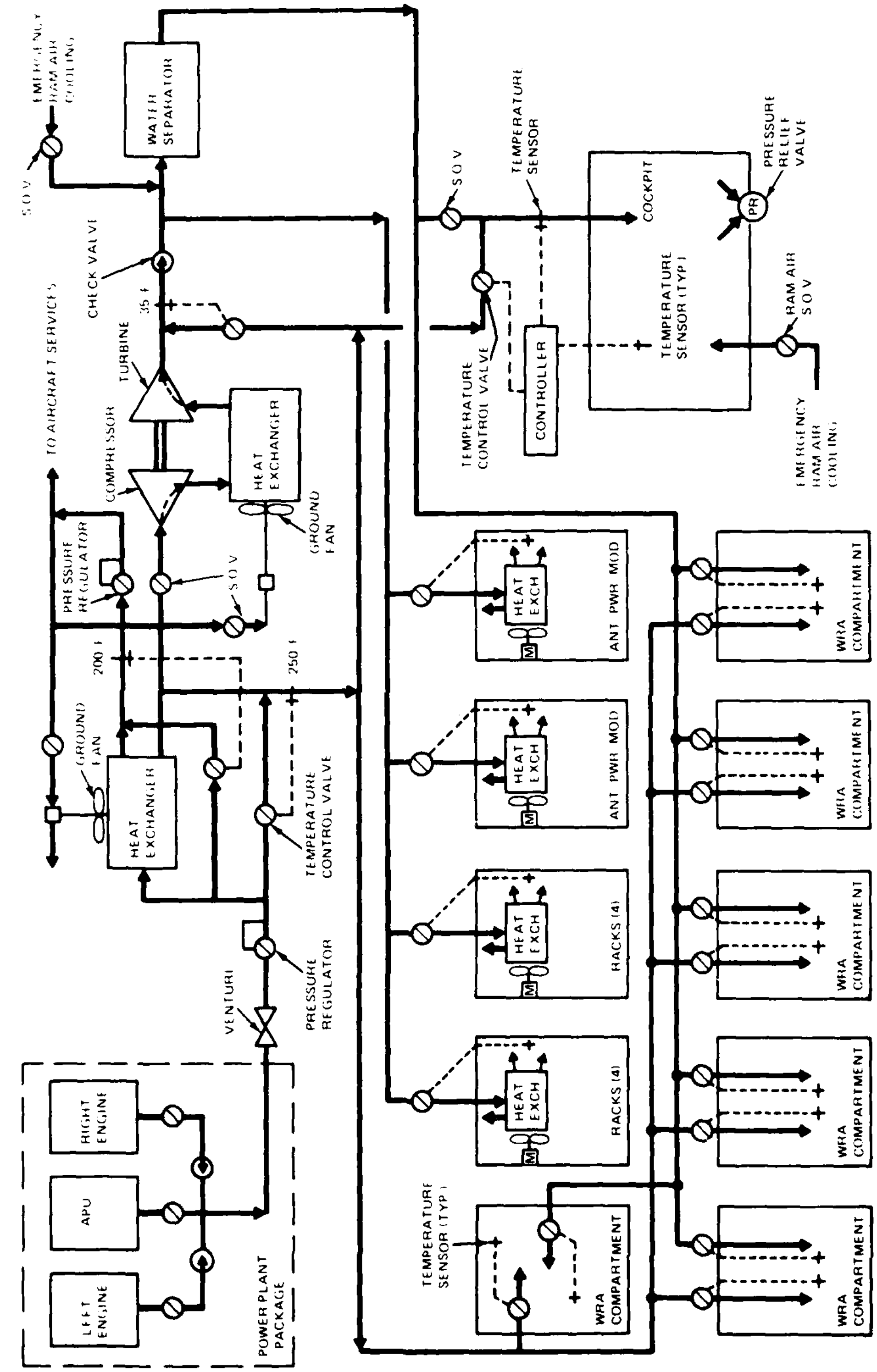

Figure 7. Bootstrap Air Cycle ECS

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Modulation of the processed bleed air for the WRA compartments is then accomplished by a temperature control system. It begins metering the processed air into the compartment only when the temperature control valve from the cooling loop air distribution loop is almost fully closed. Processed air required for cockpit temperature control, and pressurization is, on the other hand, metered by a temperature control valve which in turn is regulated in response to signals from both the cabin and the cabin-supply air temperatures. Temperature controlled 200°F air required for aircraft services is regulated via a pressure regulator.

Air Distribution Subsystem — This subsystem fulfills the cooling requirements of all the aircraft compartments and electronics by transporting and modulating the cooling air required to satisfy each cooling need. This is accomplished through the use of heat exchangers, valves, fans and sundry plumbing items. This subsystem also provides entrained moisture removal with a low pressure water separator.

The air distribution subsystem essentially removes heat by transporting and directing cool air from the air cycle machine to the three major areas requiring cooling, namely, the WRA compartments, the cockpit, and the rack and power module heat exchangers. In the racks and power modules, variable speed fans are used to force the hot air within these avionic units through built-in heat exchangers. The spent cooling air is subsequently directed overboard. For both the cockpit and the WRA compartments, though, the ECS cooling air is routed directly into these compartments. Modulation of the quantity of cooling air required by the WRA compartments is provided by temperature control valves in response to signals from their respective compartment temperature sensors.

Air Cycle Subsystem — This subsystem is the heat pump that extracts heat from the precooled bleed air, passes it on to ram air, the ultimate heat sink, and subsequently provides cooled, low pressure bleed air for distribution. It consists of heat exchangers, valves, plumbing, and a turbocompressor, and maintains a 35°F cooling-air dry-bulb temperature.

The air cycle subsystem processes bleed air by first cooling it in a heat exchanger, then compressing it in the compressor section of the air cycle

unit, further cooling it in another heat exchanger, and finally cooling it further by expansion through the turbine section of the air cycle unit. At this point in the system the cold air is reheated to a dry bulb temperature of 35°F (through the addition of bleed air), directed into the water separator for entrained moisture removal and subsequently fed into the remainder of the air distribution subsystem. From here the cold, dried air is ducted to the various areas of the aircraft for use.

Standard day bootstrap ECS performance and penalties are presented in Tables 6 and 7 for ali junction temperatures.

Table 6 Bootstrap ECS – Standard Day Performance

MISSION SEGMENT	SYSTEM WEIGHT (LBS)			BLEED AIR FLOW (LB/MIN)			RAM AIR FLOW (LB/MIN)		
	JUNCTION TEMPERATURE, °C								
	60	80	115	60	80	115	60	80	115
SEA LEVEL TAKE OFF					111.2	108.3		170.0	110.0
CLIMB OUT					86.4	113.4		142.5	87.5
CRUISE OUT AND BACK		820	756.5		72.5	52.7		108.0	75.0
LOITER					61.5	118.5		115.0	65.0
LOITER AT SEA LEVEL					98.2	95.3		171.1	113.8

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Table 7 Bootstrap ECS Weight Summary

ITEMS	JUNCTION TEMP °C	
	80	115
HEAT EXCHANGERS	259.1	225.1
TURBO-COMPRESSOR	31.0	31.0
WATER SEPARATOR	12.5	12.5
SCOOPS	23.0	20.0
FANS	93.0	93.0
DUCTING (INCL. INSUL) & PLUMBING	280.1	267.9
VALVES	67.9	62.0
CONTROLS	25.0	25.0
INSTALLATION	28.7	20.0
TOTALS	820.3 LBS	756.5 LBS

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3.2.1.2 Shoestring Air Cycle ECS - This bleed air powered ECS, shown in Fig. 8, is quite similar to the bootstrap air cycle ECS, and is also subdivided into three subsystems.

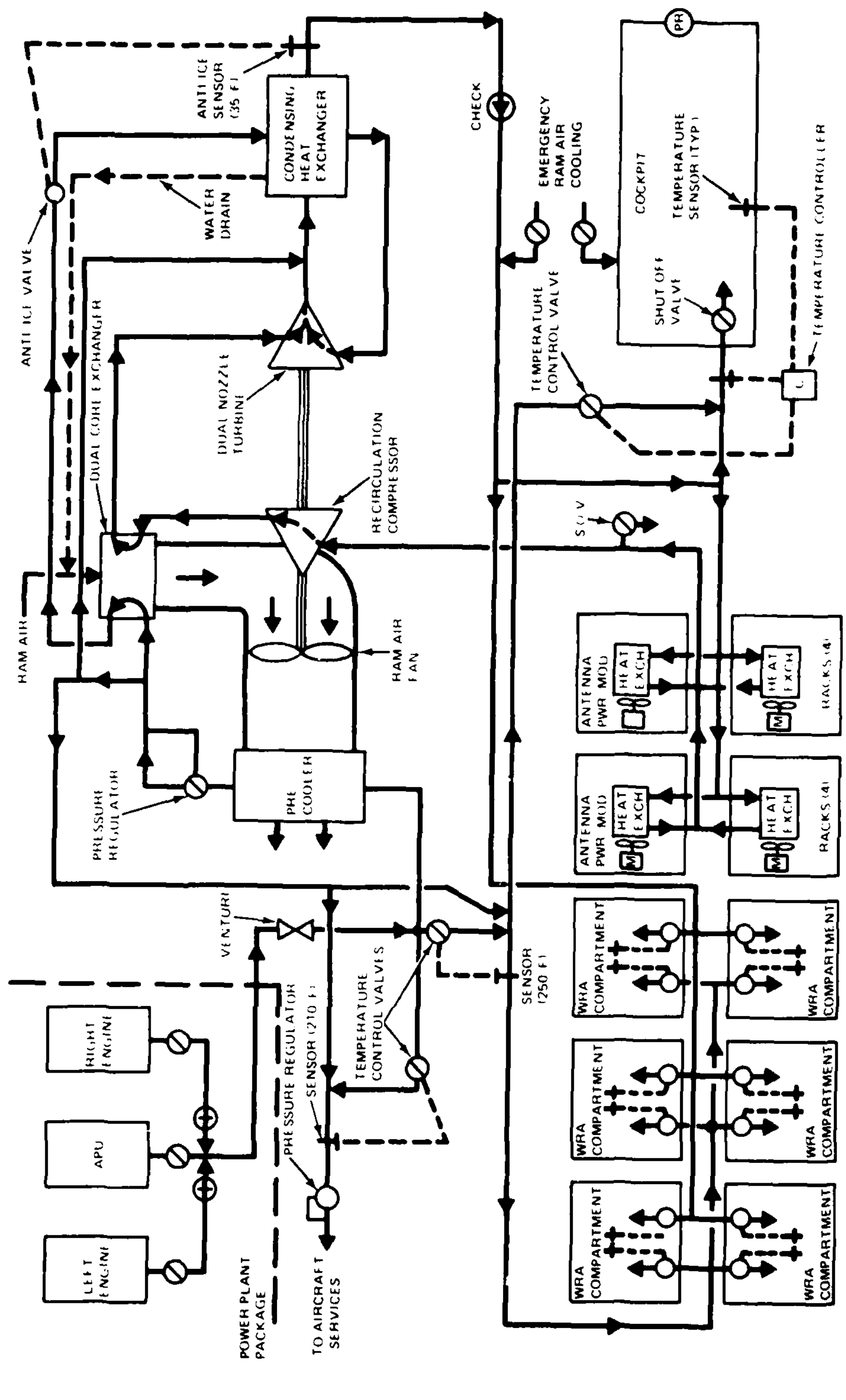

Figure 8. Shoestring Air Cycle ECS

<u>Heating & Ventilation Subsystem</u> - This subsystem is identical to that of the bootstrap air cycle ECS and functions in the same manner.

<u>Air Distribution Subsystem</u> - This subsystem is quite similar to that of the bootstrap ECS, except for return ducting from the rack heat exchangers to the air cycle subsystem.

<u>Air Cycle Subsystem</u> - This subsystem exhibits the greatest differences between the bootstrap and the shoestring concepts. As before, this subsystem is a heat pump and accomplishes the same functions, but with some differences in the hardware. Unlike the bootstrap ECS, this air cycle subsystem operates on two sources of air, namely, bleed air and recirculated cooling air. Bleed air is processed by cooling it in two heat exchangers, removing excess moisture in a condenser, then further cooling it by expansion through a turbine, and finally reheating it in the condenser cooling passages. The subsystem also both recirculates and processes recirculated cooling air by extracting it from the return lines of the air distribution subsystem's rack heat exchangers, compressing it in the compressor end of the air cycle unit, cooling it (in a heat exchanger first and then in the low pressure stage of an expansion turbine), and finally reheating it (along with the processed bleed air) in the condenser cooling passages. The mixture of processed bleed air and processed recirculated air is then directed to the air distribution system for usage. An interesting feature of the air cycle unit, aside from its two stage expansion turbine, is the fan attached to the same shaft as the compressor and turbine. This fan is used to help draw in ram air for cooling in the dual core heat exchangers.

Shoestring ECS penalties for a standard day are presented in Tables 8 and 9 for all junction temperatures. In comparison to the bootstrap ECS, the shoestring ECS is slightly lighter, consumes less bleed air, but requires more ram air for cooling. Power consumption is about the same as for the bootstrap ECS.

3.2.1.3 <u>Vapor Cycle System ECS</u> - This ECS is comprised of three major subsystems, as shown in Fig. 9 and 10, namely: the heating and ventilating, liquid cooling and vapor cycle subsystems.

Table 8 Shoestring ECS – Standard Day Performance

MISSION SEGMENT	SYSTEM WEIGHT (LBS)			POWER CONSUMPTION (KW)			BLEED FLOW (LB/MIN)			RAM FLOW (LB/MIN)		
	JUNCTION TEMPERATURE C											
	60	80	115	60	80	115	60	80	115	60	80	115
SEA LEVEL TAKEOFF				4.6	3.0	2.5	107	73	52	641	306	270
CLIMB OUT				5.5	3.3	2.8	80	55	40	458	237	220
CRUISE OUT AT 33K				8.4	5.2	4.7	51	36	27	344	210	212
LOITER AT 35K	904	757	670	6.3	3.6	3.1	52	37	28	274	168	169
CRUISE BACK AT 42K				11.3	7.3	6.8	50	35	26	269	166	167
LOITER AT SEA LEVEL				4.6	3.0	2.5	96	64	52	692	383	366

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Table 9 Shoestring ECS Weight Summary

ITEMS	JUNCTION TEMP C 60	80	115
HEAT EXCHANGERS	328	275	244
TURBO-COMPRESSOR FAN ASSY	94	64	46
CONDENSER SEPARATOR	13	9	6
SCOOPS	21	14	10
FANS	86	77	77
DUCTING & PLUMBING	216	195	166
VALVES	53	50	54
CONTROLS	39	37	41
INSTALLATION	54	36	26
TOTAL	904 LBS	757 LBS	670 LBS

0442-014D

Heating & Ventilation Subsystem – This subsystem consists primarily of a heat exchanger, temperature and pressure control valves, fans and plumbing. It provides temperature controlled bleed air to both the cockpit and WRA compartments to satisfy their ventilation and/or heating requirements.

The heating and ventilation subsystem, whose configuration remains the same regardless of junction temperature, processes bleed air to the required temperature level and modulates the quantity supplied to the compartments. Processing of the bleed air is accomplished by a ram air heat exchanger which

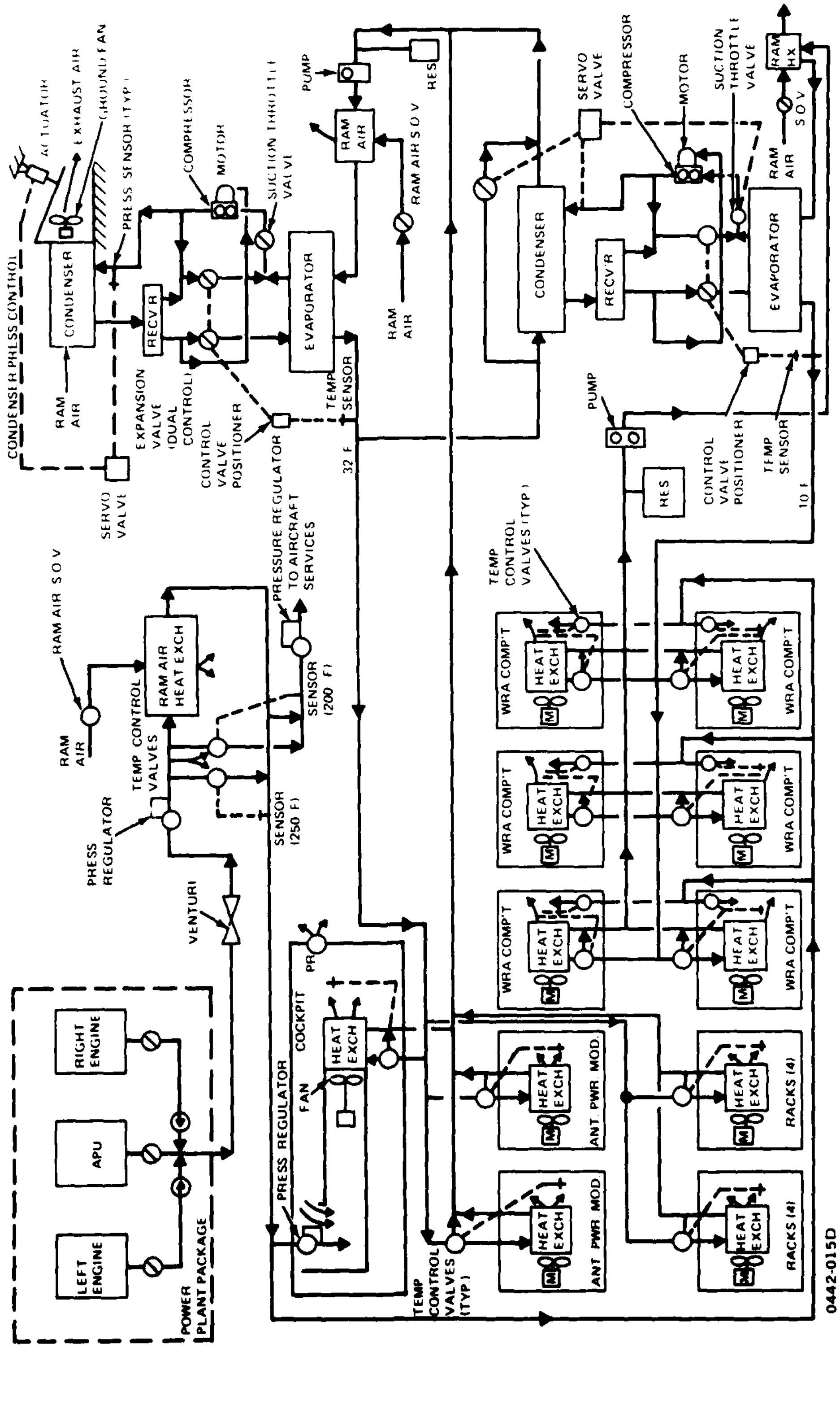

Figure 9. Vapor Cycle ECS - $T_{Junction}$ = 60°C

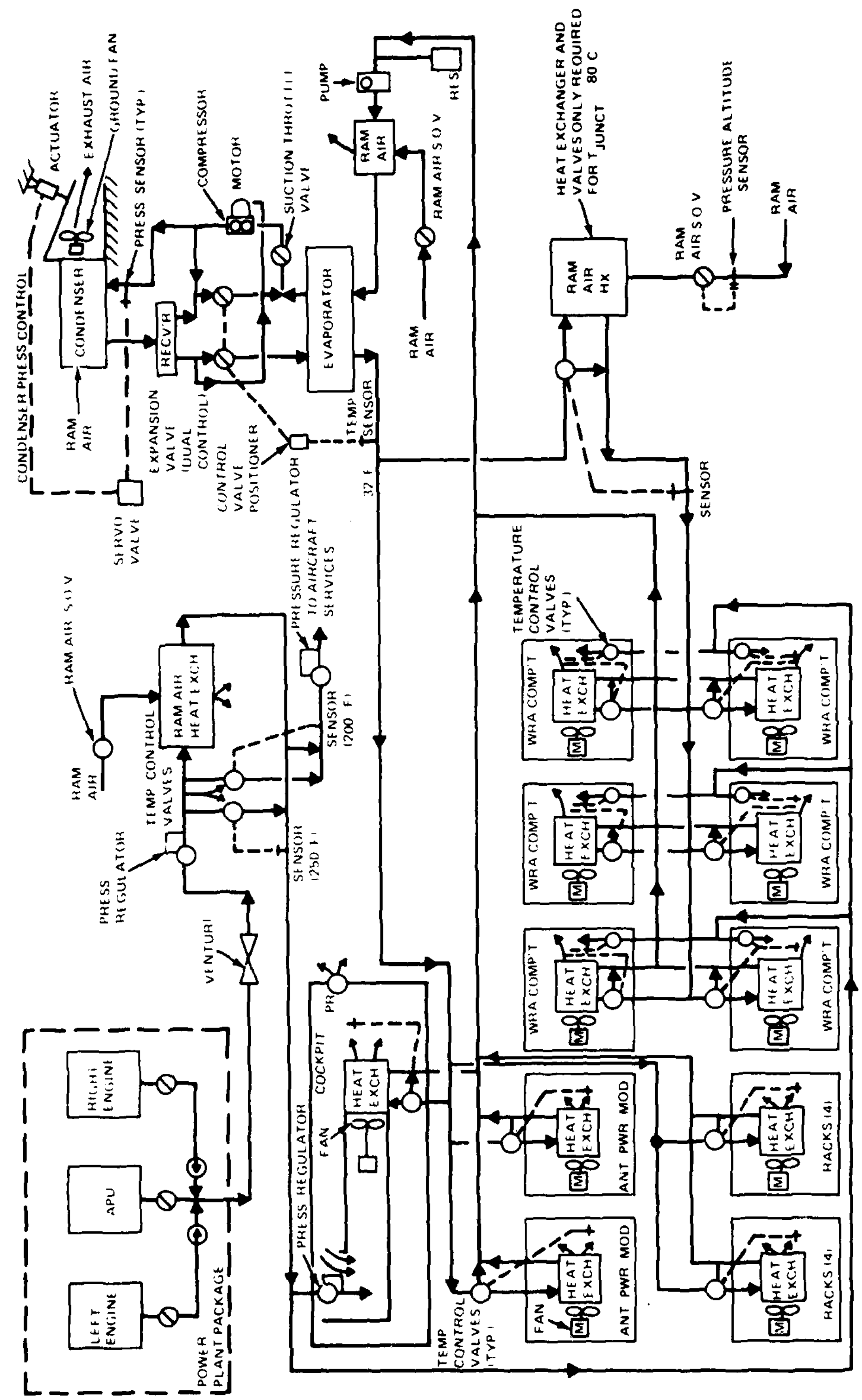

Figure 10. Vapor Cycle ECS - $T_{Junction} = 80^{\circ}C$ & $115^{\circ}C$

cools the bleed air to temperatures below 200°F, and temperature control valves which meter quantities of raw bleed air to adjust mixture temperatures to 250°F for the WRA compartments and to 200°F for the remaining aircraft services (e.g., defog). Modulation of the processed bleed air quantity for the WRA compartments is accomplished by a temperature control system. It begins metering the processed bleed air into the compartment only when the temperature control valve in the liquid heat transport loop is fully bypassing the liquid coolant around the compartment heat exchanger. Variable speed fans located in each of the WRA compartments provide the air circulation required for compartment ventilation. Processed air required for cockpit ventilation, heating, and pressurization is, on the other hand, metered by a pressure regulator in the cockpit supply line. A pressure regulator is also used to meter the 200°F air required for aircraft services.

Liquid Cooling Subsystem —This subsystem fulfills the cooling requirements of all aircraft compartments by transporting and modulating the cooling fluid required to satisfy each compartment's cooling needs. Consisting of pumps, heat exchangers, temperature control valves, and sundry plumbing items, this subsystem pumps the warmed heat transport fluid from each of the compartments to the vapor cycle subsystem which serves as a heat sink.

The liquid cooling subsystem essentially removes heat from the cockpit, racks, antenna power-modules, and the WRA compartments by pumping cold Coolanol 25, the heat transport fluid, from the vapor cycle subsystem through the heat exchangers located in each of the heat producing areas. Unlike the heating and ventilation subsystem the liquid cooling subsystem configuration changes with junction temperature. For a 60°C junction temperature the WRAs are provided with -10°F coolanol temperatures while the remainder of the cooling is done with coolanol at 32°F. This is accomplished by having two distinct cooling loops, i.e., one for the WRAs alone and another to cool the remaining items. As shown in Fig. 10, however, for the 80°C and 115°C junction temperature cases, the cooling loops are almost identical. The only difference between the two is the addition of a ram air heat exchanger for the 80°C junction temperature case. It is used to provide supplemental coolanol cooling at altitudes above 35,000 feet in order to achieve temperatures low enough (i.e., less than 32°F) to satisfy the WRA cooling requirements.

There is only a single cooling loop in both the 80°C and 115°C configurations and all heat is transferred to the coolant in the manner described previously for the 60°C junction temperature configuration. In all three configurations temperature control valves are used to bypass coolant around the heat exchangers for temperature control. Temperature sensors located at the outlet of the heat exchangers (for both racks and antenna power modules) or in the compartments (for the WRAs and the cockpit) provide the signal inputs required by their respective temperature control valves.

Vapor Cycle Subsystem – This subsystem is the heat pump which absorbs the heat from the liquid cooling subsystem at a low temperature level, and releases it at a higher temperature level to ram air which is the ultimate heat sink. As shown in the schematics, the subsystem concept for 60°C junctions is different than the remaining two. The latter have a single vapor cycle unit whereas the former uses two units. For the former, one unit handles the WRA heat transport loop alone (and provides the low coolant temperatures required for the WRA compartments) and the other handles the remaining heat transport loop (which acts as sink not only for the racks, cockpit and power modules but also for the condenser of the vapor cycle unit handling only the WRA loads). In both cases, the heat transmission process occurs with a Freon working fluid which absorbs heat in the evaporator and releases heat in the condenser. A compressor circulates the fluid between the two units. In the condenser, the heat is transferred to the external ram air, the ultimate heat sink.

Freon 21 is the refrigerant used for the primary (i.e., the larger) unit while Freon 12 is used in the smaller unit. Different Freons were selected because of the major differences in condensing and evaporating temperatures between the two vapor cycle units. Freon 21, in contrast to Freon 114, was selected because it resulted in a unit that weighed less and consumed less power. However, it is a difficult fluid to contain because of its tendency to leak. From an academic standpoint Freon 21 was best and Freon 114 second best of the several Freons investigated. From a practical standpoint Freon 114 would probably be used if a vapor cycle system were the system of choice. This would increase the vapor cycle system weight and power penalties and make this system even less attractive than shown here.

Vapor cycle system penalties for a standard day are presented in Tables 10 and 11 for all junction temperatures. Of significance is the markedly higher power consumption and the marked increase in weight associated with the system designed for a 60°C junction temperature. The cause of this is the need for a second vapor cycle unit to satisfy the WRA requirements at the 60°C junction temperatures during flight at high altitudes. The differences between the 80°C and the 115°C systems merely reflect the increased cooling requirements at the lower junction temperature.

Table 10 Vapor Cycle ECS –Standard Day Performance

MISSION SEGMENT	TOTAL SYSTEM WEIGHT (LBS)			POWER CONSUMPTION (KW)			RAM FLOW (LB/MIN)			BLEED FLOW (LB/MIN)		
	JUNCTION TEMPERATURE C											
	60	80	115	60	80	115	60	80	115	60	80	115
SEA LEVEL TAKEOFF	2319	1647	1427	76	54	41	247	297	183	4	4	20
CLIMBOUT				77	56	42	170	214	132	5	5	13
CRUISE OUT				83	57	44	98	136	85	6	6	6
LOITER AT 35K				79	55	42	93	125	81	6	6	6
CRUISE BACK				88	60	46	99	128	87	6	6	6
LOITER AT SEA LEVEL				76	54	41	247	302	183	4	4	20

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Table 11 Vapor Cycle ECS Weight Summary

ITEMS	JUNCTION TEMP C		
	60	80	115
CONDENSER-EVAPORATOR-COMPRESSOR ASSY	688	486	402
SCOOPS	169	147	116
HEAT EXCHANGERS	394	352	317
FANS	234	138	105
DUCTING & PLUMBING	88	115	130
PUMP, FILTERS, RESERVOIRS, MISC	595	268	222
VALVES	19	28	31
CONTROLS	30	30	30
ELEC PWR GEN WT PENALTY	102	83	74
TOTAL *	2319 LBS	1647 LBS	1427 LBS

*INSTALLATION INCLUDED

0442-018D

3.2.1.4 Positive Displacement Closed Loop Air Cycle, ECS - The system, shown in Fig. 11, is quite similar to the vapor cycle ECS. The major difference is that the vapor cycle unit is replaced by a positive displacement closed air cycle unit; both the heating and ventilation subsystem and the liquid cooling subsystem are identical in both systems. Only the operating temperature of the heat transport fluid is different in the air cycle based system. The closed loop air cycle subsystem, acting much like a vapor cycle unit, basically removes the heat (with air) from the heat transport subsystem and delivers it to ram air, the ultimate heat sink. The unit accomplishes this by absorbing heat from the liquid coolant in an air/liquid heat exchanger and transmitting it via a compressor/expander section to a ram air cooled heat exchanger. The compressor/expander is a positive displacement device that operates much like a rotary, sliding vane pump. However, unlike the pump, both air compression and expansion occur in the same housing. Air enters the compressor half of the unit, is compressed to a high temperature and pressure, then enters the ram air heat exchanger where it is cooled, then enters a regenerative heat exchanger where it is cooled further, then finally enters the expander section where it's pressure and temperature are decreased. The air, extremely cold at this point, is then directed to the air/liquid heat exchanger to cool the system heat transport fluids. The compressor/expander is driven by a hydraulic motor at approximately 3000 rpm, and requires special cooling provisions for its end caps and stator. This is provided by a liquid cooling system which (in this study) is separate from the main heat transport loop and is considered to be part of the air cycle subsystem.

Standard day closed loop ECS performance and penalties are presented in Tables 12 and 13 for all junction temperatures*. In comparison to the closed vapor cycle ECS, this air cycle ECS, although it consumes more power and

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*Compressor-expander efficiencies used as the basis for the performance and penalty estimates are based on preliminary projections from the U.S. Air Force Flight Dynamics Laboratory's Positive Displacement Air Cycle Machine Program.

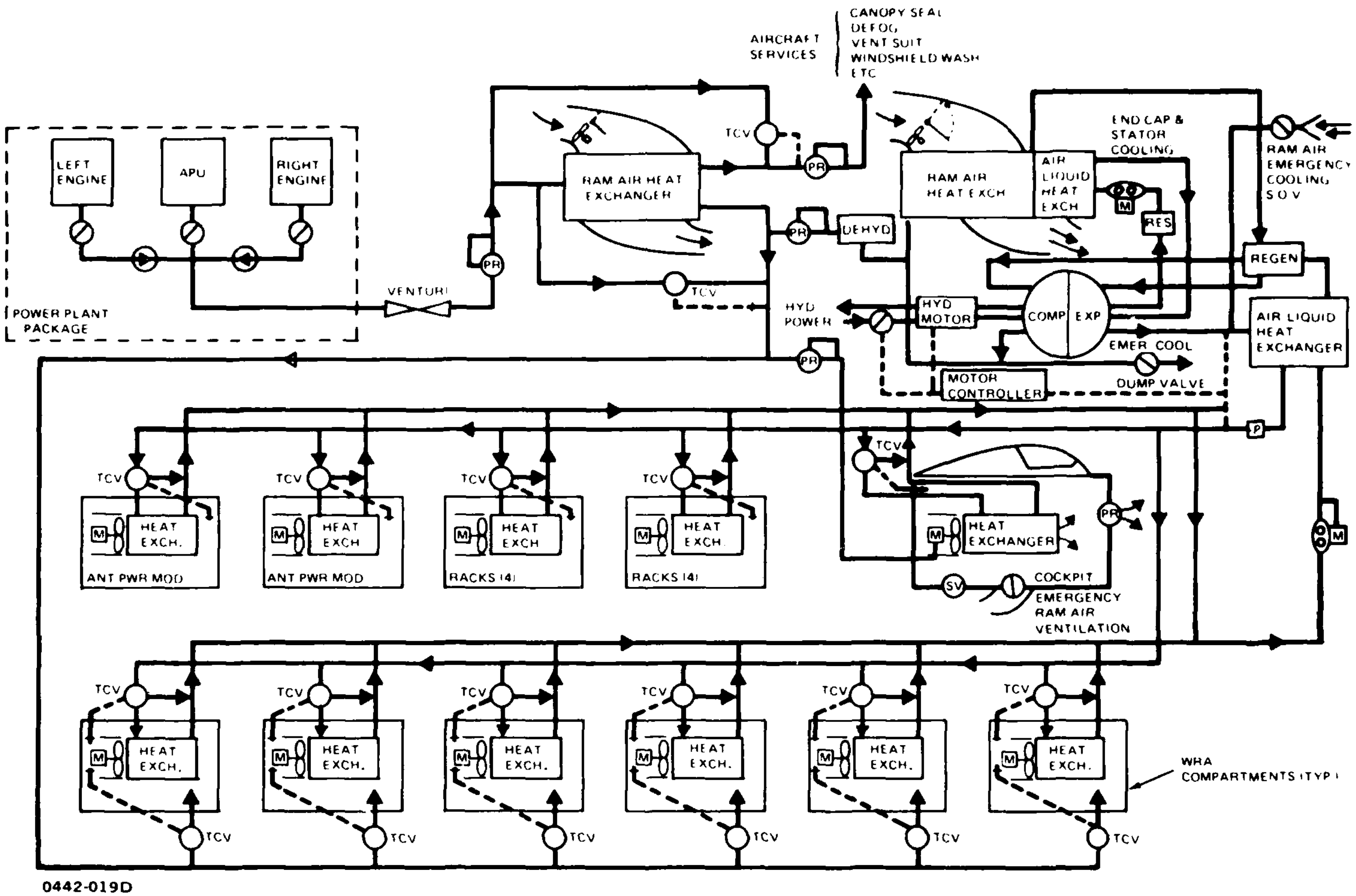

Figure 11. Closed Loop Air Cycle ECS (Pos Displ).

Table 12 Closed Loop Positive Displacement ECS – Standard Day Performance

MISSION SEGMENT	TOTAL SYSTEM WEIGHT (LBS)			POWER REQUIREMENTS (KW)			RAM AIR FLOW (LBS/MIN)			BLEED AIR FLOW (LBS/MIN)		
	JUNCTION TEMPERATURE C											
	60	80	115	60	80	115	60	80	115	60	80	115
SEA LEVEL TAKEOFF	1632.3	1198.1	1073.0	133.9	102.4	76.1	560	300	280	5.4	5.4	21.1
CLIMB OUT				117.4	87.9	71.6	470.0	251.0	234	6.1	6.1	14.0
CRUISE OUT & BACK				104.5	84.9	78.0	360	190	176	6.1	6.1	6.1
LOITER AT ALT.				100.9	73.4	67.1	380	202	188	6.8	6.8	6.8
SEA LEVEL LOITER				112.6	91.5	77.0	760	414	390	5.4	5.4	5.4

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Table 13 Closed Loop Positive Displacement – Weight Summary

ITEMS	JUNCTION TEMP °C		
	60	80	115
HEAT EXCHANGERS	358	293.9	225.9
TURBO COMPRESSOR FAN ASSY	310	208	186
PUMP, FILTERS, RESERVOIR, MISC.	381.6	236.5	197.4
SCOOPS	23	13	13
FANS	224	155	155
DUCTING & PLUMBING	85.1	112.4	128.1
VALVES	15.1	13.8	13.0
CONTROLS	30	30	30
INSTALLATION	101	72.4	59.6
HYDRAULIC SYS. WT. INCREASE	105	73	65
TOTAL	1632.8 LBS	1198.0 LBS	1073 LBS

0442-021D

requires more ram air, is significantly lighter, so that its total aircraft penalty is smaller than that of the vapor cycle ECS. In contrast to the open and partially closed ECS, this air cycle ECS consumes less bleed air, but utilizes more power and ram air and is significantly heavier.

3.2.1.5 <u>Centrifugal Closed Loop Air Cycle ECS</u> - This electrically driven centrifugal driven air cycle ECS, shown in Fig. 12, is identical to the closed loop ECS previously described except for the hardware used for the air cycle unit. In this ECS a high speed centrifugal air cycle machine is

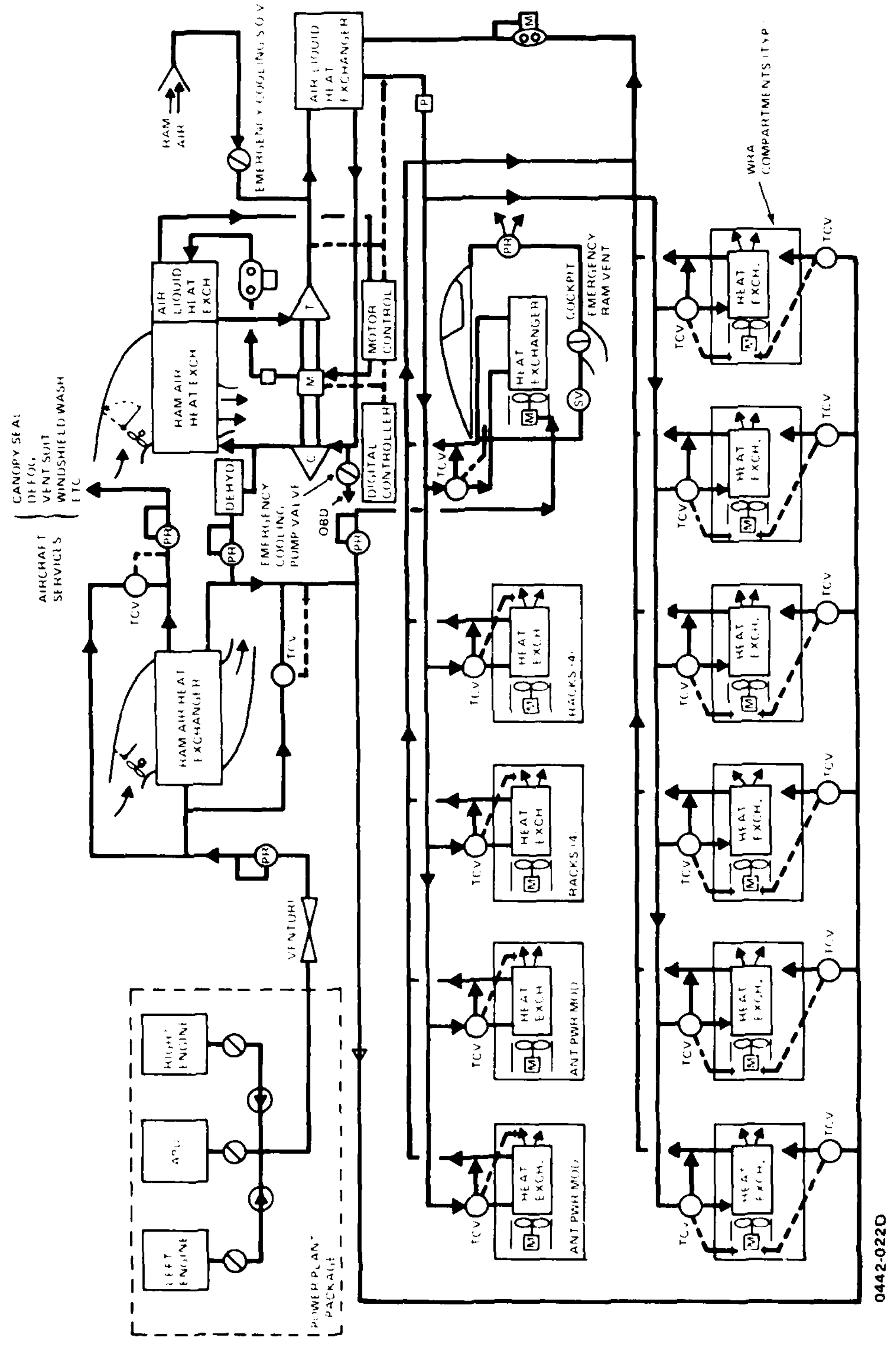

Figure 12. Closed Loop Air Cycle (Centrifugal) ECS

used for air compression and expansion. The high speeds are obtained by the use of electrically driven, high frequency motors. Power conditioning equipment is used to convert the 270 Volt DC power to the high frequency power required for driving the electric motors. Cooling of the motor electronics is provided by a special liquid cooling system.

Standard day centrifugal closed loop ECS performance and penalties are presented in Tables 14 and 15 for all junction temperatures. In comparison to its closest competitor, the positive displacement closed loop ECS, the centrif-

Table 14 Closed Loop (Centrifugal) ECS – Standard Day Performance

MISSION SEGMENT	TOTAL SYSTEM WEIGHT (LBS)			POWER REQUIREMENTS (KW)			RAM AIR FLOW (LBS/MIN)			BLEED AIR FLOW (LBS/MIN)		
	JUNCTION TEMPERATURE °C											
	60	80	115	60	80	115	60	80	115	60	80	115
SEA LEVEL TAKEOFF				122.0	103.2	88.6	280.0	150.0	140.0	5.4	5.4	21.1
CLIMB OUT				81.5	68.5	60.5	235	125.5	117.0	6.1	6.1	6.1
CRUISE OUT & BACK	1550.2	1127.6	1011.7	50.4	42.6	40.6	180.0	95.0	88.0	6.8	6.8	6.8
LOITER AT ALT.				41.0	33.8	32.3	190.0	101.0	94.0	6.8	6.8	6.8
SEA LEVEL LOITER				106.5	82.2	73.0	380.0	207.0	195.0	5.4	5.4	21.1

0442-023D

Table 15 Closed Loop Centrifugal ECS – Weight Summary

ITEMS	JUNCTION TEMP °C		
	60	80	115
• HEAT EXCHANGERS	353	278	220
• TURBO COMPRESSOR ASSY	237	152	135
• FANS	209	140	140
• DUCTING & PLUMBING	85.1	112.4	128.1
• SCOOPS	23	13	13
• PUMPS, FILTERS, RES	312	186	153
• VALVES	15.1	13.8	13
• ELEC PWR GEN	185	130	120
• CONTROLS	30	30	30
• INSTALLATION	101	72.4	59.6
TOTALS	1550.2 LBS	1127.6 LBS	1011.7 LBS

0442-024D

ugal air cycle ECS is slightly lighter, consumes slightly less power and requires less ram air; its total aircraft penalty is also slightly less.

3.2.2 ECS Comparisons

TOGW was used as the common denominator so that a proper comparison could be made between the systems even though their weight, power consumption, ram air, etc. penalties differed. In effect, for each ECS concept and its associated penalties, an aircraft was sized to perform the AEW mission and its resultant TOGW established. The sizing was done by an inhouse Grumman program known as CISE (Computerized Initial Sizing Estimate).

The results of the CISE Program aircraft sizing efforts are shown in Fig. 13 where the ECS TOGW penalty is plotted for different junction temperatures. In this instance the ECS TOGW penalty is the increase in aircraft weight due to all the penalties associated with the ECS.

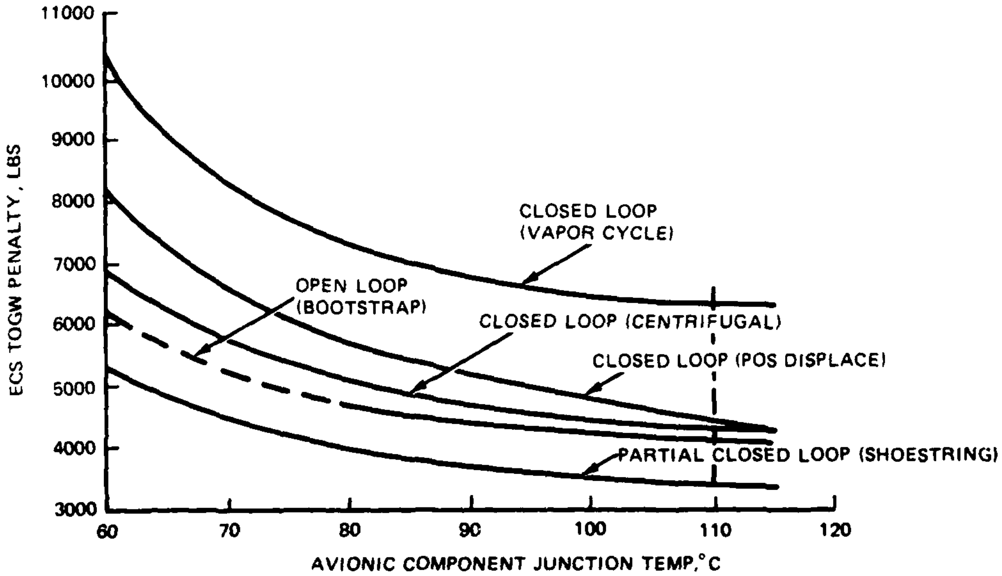

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Figure 13. V/STOL TOGW Variation

It is observed from Fig. 13 that the optimum system is the partially closed loop shoestring air cycle which uses less bleed air then the next best ECS, the open loop bootstrap air cycle. The closed loop systems, even though they only consume a small amount of bleed air, are by far the heavi-

est systems and result in the largest aircraft penalties. They therefore are the least desirable.

Another interesting observation from the figure is the increase in all penalties with decreasing junction temperature. Designing for a 60°C junction rather than a 115°C junction results in at least a 50% increase in ECS TOGW penalty. Also the TOGW penalty increases most rapidly at junction temperatures below 80°C.

The reliability and maintainability (R&M) characteristics of the five ECS concepts were also evaluated. The ECS component failure rates were obtained from both the **Nonelectronic Reliability Notebook** (Ref 3) and actual Grumman ECS data and engineering estimates. The mean time to repair (MTTR) were derived from estimations of times required for fault detection, fault isolation, and removal, replacement, and checkout of each component. The mean time between failures (MTBF) of all concepts except the vapor cycle were found to be insensitive to junction temperature with little or no effect on the reliability prediction. The vapor cycle, however, required an additional loop to achieve the lower junction temperatures, thereby decreasing the MTBF. The detail R&M analysis is presented in Appendix B, and a summary of the results is shown in Table 16. Reference 4 was used in this portion of the study to obtain fleet values from predicted values.

Table 16 ECS R&M Summary

ECS CONCEPT	JCT TEMP, °C	PREDICTED MTBF, HR	FLEET MTBF, HR	FLEET MTBM, HR	MTTR, HR
BOOTSTRAP AIR CYCLE	60 80 115	170	57	19	1.09
SHOESTRING AIR CYCLE	60 80 115	177	59	20	1.08
VAPOR CYCLE	60 80 115	112 131 131	37 44 44	12 15 15	1.05
POSITIVE DISPLACEMENT CLOSED-LOOP AIR CYCLE	50 80 115	144	48	16	1.08
CENTRIFUGAL CLOSED-LOOP AIR CYCLE	60 80 115	142	47	16	1.06

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The summary indicates that the preferred ECS concept from a reliability point of view is the shoestring ECS closely followed by the bootstrap system. The least reliable ECS concept is the vapor cycle. This is especially true at the lower junction temperatures because of its greater complexity.

Ground cooling of the aircraft was investigated with both on-carrier-deck and below-carrier-deck (i.e., hangar deck) operation being considered. All ECS concepts were found to require either main engine or APU usage for on-deck operations. Hangar deck operations require different ship support systems for the various ECS concepts. The bootstrap and shoestring ECS concepts require either aircraft APU or the ship's pneumatic power to supply the high pressure air that is required for ECS operation. In lieu of this, the ship's cooling air can be ducted to the aircraft air distribution system and the aircraft cooled directly. For the vapor cycle and centrifugal closed loop ECS concepts, only the aircraft APU or the ship's electrical power is required for the ECS to operate and provide cooling. The positive displacement closed loop air cycle ECS requires either EPU usage or a combination of the ship's hydraulic and electrical power. For hangar deck operation, both the vapor cycle and centrifugal closed loop air cycle ECS concepts have the simplest interface requirements, because only an electrical connection is required.

A summary of the characteristics of each ECS concept is given in Table 17. When the remarks made for the partially closed shoestring ECS are considered along with the knowledge that such a system has the lowest TOGW penalty, then on a non-cost basis closed loop air cycle and closed loop vapor cycle systems do not merit serious consideration.

Table 17 Assessment of Concepts

CONCEPT	R & M	SAFETY/VULNERABILITY	DEVELOPMENT RISK
OPEN LOOP (BOOTSTRAP)	• HIGH RELIABILITY • LOW COMPLEXITY • NO INTERMEDIATE COOLING LOOP	• LEAK TOLERANT • NON HAZARDOUS WORKING FLUID (AIR)	• LOWEST – PRESENT DAY TECHNOLOGY
PARTIALLY CLOSED LOOP (SHOE STRING)	• HIGHEST RELIABILITY • LOW COMPLEXITY • MINIMAL INTERMED.	• LEAK TOLERANT • NON HAZARDOUS WORKING FLUID (AIR)	• LOW – ADVANCED STATE-OF-ART TECHNOLOGY
CLOSED LOOP (CENTRIFUGAL)	• LOWER REL. THAN ABOVE CONCEPTS • REQUIRES INTERMED. HEAT TRANSPORT LOOP • INCREASED SYST. COMPLEXITY	• REFRIG. CIRCUIT LEAK TOLERANT • INTERMED. HEAT TRANSPORT LOOP LEAKAGE CAN RESULT IN SYST. FAILURE	• HIGH – REQUIRES NEW HIGH SPEED, HIGH POWER MOTOR DEVELOPM'T.
CLOSED LOOP (POSITIVE DISPLACEMENT)	• SAME AS CLOSED LOOP (CENTRIFUGAL)	• SAME AS CLOSED LOOP (CENTRIFUGAL)	• HIGHEST – NEW TECHNOLOGY, AIR CYCLE DEVELOPMT. INCLUDING MULTIPLE BEARINGS & SLIDING VANES
CLOSED LOOP (VAPOR CYCLE)	• LOWEST RELIABILITY • SYSTEM COMPLEXITY SENSITIVE TO DECREASING AVIONIC JUNCTION TEMPERATURE • HIGHEST NUMBER OF COMPONENTS	• FREON REFRIGERANT CAN BE TOXIC WHEN SUBJECT TO OVERTEMPERATURES • FREON LEAKAGE CAN CAUSE SYSTEM FAILURE • INTERMED. LIQUID HEAT TRANSPORT LOOP LEAKAGE CAN RESULT IN SYSTEM FAILURE	• MODERATE – HIGH SPEED ELECTRICALLY DRIVEN FREON COMPRESSORS HAVE PRIOR AIRCRAFT APPLICATION

0442-027D

4 - LIFE CYCLE COST INVESTIGATIONS

4.1 METHODOLOGY

These cost studies consisted of determining (and comparing) total aircraft program Life Cycle Costs (LCC) for aircraft sized and designed to operate with each of the ECS concepts investigated. Each aircraft/ECS concept combination studied was designed for three junction temperatures. In effect, every ECS concept/junction temperature combination resulted in a different aircraft size and, consequently, in a different program LCC.

All aircraft features except avionics were allowed to increase (or decrease) in size as required for each aircraft/ECS concept/junction-temperature combination. Thus, aircraft structure, powerplants, fuel systems, etc. were all allowed to grow as necessary to accommodate each particular ECS. As a result, the Research Development, Test & Evaluation (RDT&E), production, operation, etc. costs all vary for each concept/junction-temperature combination. Therefore, program LCC are different for each.

The methodology for generating the life cycle costs for the aircraft makes use of two Grumman cost models. They are the modular life cycle cost model (MLCCM) which generates all aircraft life cycle costs other than those associated with the ECS and the avionics, and the subsystem LCC model which assesses ECS and avionics costs.

The MLCCM (see Table 18) is a computerized methodology, developed by Grumman under contract to the U. S. Air Force, for predicting and conducting life cycle cost assessments during the conceptual and preliminary design stages of a new aircraft development program. The MLCCM, which contains design-sensitive cost estimating relationship at the subsystem level, is incapable of assessing the sensitivity of life cycle costs to subsystem's reliability.
To compensate for this insensitivity, use was made of the subsystem life cycle cost model to gauge the reliability effects on ECS and avionics costs.

Table 18 Modular Life Cycle Cost Model (MLCCM)

SUBSYSTEM / COST ELEMENTS	STRUCTURES					CREW SYSTEM	LANDING GEAR	FLIGHT CONTROLS	ENGINE	ENGINE INSTALLATION	ECS	ELECTRICAL	HYDRAULIC/ PNEUMATIC POWER	FUEL SYSTEM	AVIONICS	ARMAMENT	CARGO HANDLING	OTHER		TOTAL
WUC	11,92					12,16.49 91,96.97	13.93	14	22 & 32 OR 23	24.20	41.47	42 44 51	45	46	52.65 56.74 76.77	75				
	WING	BODY	TAIL	NACELLE	TOTALS													FINAL ASSY	SUST'G	
• RDT&E																				
– AIRFRAME																				
ENGINEERING																				X
MANUF/Q.C.																				X
TOOLING																				X
TOTAL																				X
– AVIONICS															X					
– ENGINES									X											
• PRODUCTION																				
– AIRFRAME	X	X	X	X		X	X	X		X	X	X	X	X		X	X	X	X	
– AVIONICS																X				
– ENGINES									X											
• INITIAL SUPPORT																				
– SPARES					X	X	X	X	X	X	X	X	X	X	X	X				
– SUPPORT EQUIP.					X	X	X	X	X		X		X	X	X	X				
– CONTRACTED TRAINING																	(X)			X
– DATA					X	X	X	X	X	X	X	X	X	X	X	X				
• OPERATIONS & SUPPORT																				
– BASE LEVEL MAINTENANCE					X	X	X	X	X	X	X	X	X	X	X	X	(X)			
– BASE LEVEL OPS. PERS.																				X
– BASE LEVEL TRG PERS.																				X
– DEPOT AIRFRAME (PDM)																				X
– DEPOT COMP. REPAIR						X	X	X		X	X	X	X	X	X		(X)			
– DEPOT ENGINE REPAIR									X											
– REPLENISHMENT SPARES					X	X	X	X	X	X	X	X	X	X	X		(X)			
– POL																				X
– OTHER																				X

(X) CER'S DEVELOPED FOR CARGO AIRCRAFT ONLY

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The subsystem LCC model (see Table 19) is a Grumman-adapted, computerized Air Force methodology for predicting acquisition and logistic support costs. It is an analytical model programmed for computer application and it consists of a series of equations for calculating costs of selected acquisition and logistic requirements of an aircraft program.

Table 19 Subsystem LCC Model – ECS and Avionics

R,D,T & E	AQUISITION		D & S
	PRODUCTION	INITIAL SUPT	
REDUCE ADVANCED DEVELOPMENTS TO PRACTICE**	NON RECURRING MFG*	SPARES (IOL)*	REPLENISHMENT SPARES*
		PUBS	
	RECURRING MFG*	TRAINING	MAINTENANCE LABOR (0 & I)*
	ENGINEERING	SUPPORT EQPMT	OPERATIONAL PERSONNEL
			SDLM
			ENGINE OVERHAUL
			FUEL
			DEPOT REPAIR*
0442-030D			SHORE SITE OPS & OVERHEAD*

*INCLUDED IN ANALYSIS
**INCLUDED IN ECS SUBSYSTEM ANALYSIS ONLY

Both models include RDT&E, production, initial support, and operations and support costs. The total LCC for a given concept at a specific junction temperature is equal to the sum of the LCC from each of the two models (see Fig. 14).

4.2 LCC GROUND RULES AND ASSUMPTIONS

The first step in setting up the LCC study was to establish ground rules and a scenario for the AEW V/STOL aircraft. The scenario used was based on Grumman's design in which the aircraft were deployed to three classes of sites with the following complement of aircraft:

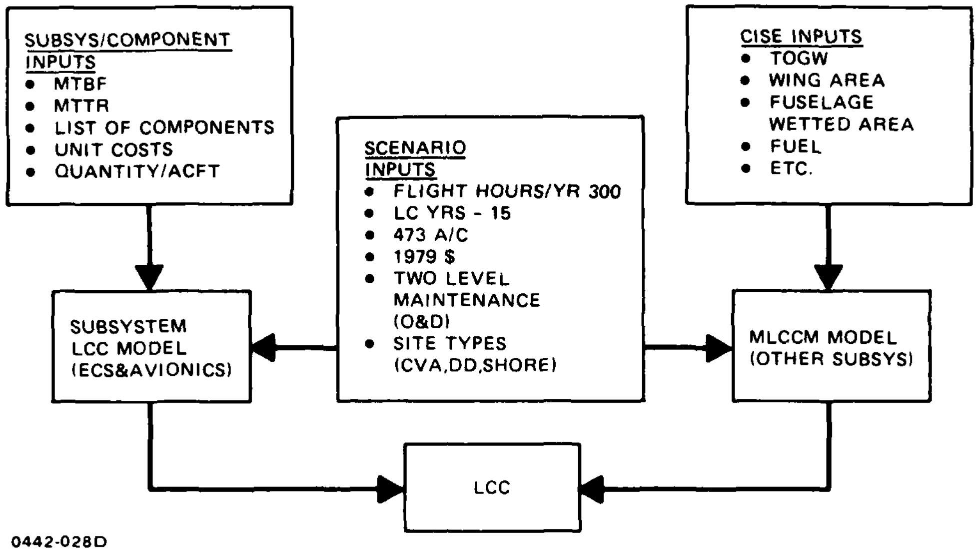

Figure 14. LCC Model Inputs

LARGE SHIPS (carriers)

4 CV's with 18 aircraft each

SMALL SHIPS

20 DD-963's with 2 aircraft each

SHORE SITES

6 Shore sites with 42 aircraft each

The total of 364 operational aircraft was used in both cost models. This total was escalated to 473 production aircraft to account for Standard Depot Level Maintenance (SDLM) and attrition aircraft requirements.

Key assumptions and ground rules included in the analysis were:

- 15 years life cycle
- Peacetime operation
- 25 flight hours per month per aircraft during normal operation
- 10% expected backorder level for spares (90% probability of no stock-out at O-level)
- 2 level maintenance - aircraft level and depot level. Remove and replace (R&R) only maintenance at aircraft level, all other repair at depot level

- Depot consumable materials used at a rate of $5.19 per hour of repair (typical of past observed depot consumable material costs)
- Depot turn-around time for repair of avionics is 1.8 months
- All costs in 1979 dollars
- No scheduled maintenance is required for the ECS and the rack avionics.

4.3 RESULTS

4.3.1 ECS Life Cycle Costs

Both RDT&E and production unit costs for the ECS were estimated by Grumman in conjunction with various subcontractors. Each ECS was broken down into its major components for calculation of acquisition and O&S costs. Each ECS component cost was estimated to include repair material and labor costs over the life cycle. The additional costs to stock and repair lower level assemblies were accounted for by adding 1% of the major unit cost to each repair action.

The results of the ECS subsystems study effort alone are compared in Fig. 15. It can be observed that production costs are clearly the drivers, accounting for approximately 76% of the direct LCC of each ECS concept. The initial support and O&S costs are relatively low due to the high reliability of each ECS concept. Furthermore, it appears that the open loop bootstrap and shoestring ECS concepts are one-third to one-half less costly than the closed loop ECS concepts.

4.3.2 Avionics Life Cycle Costs

The avionics consisted of 16 WRAs plus 8 racks containing electronic modules. There are four generic rack module types: memory, digital, analog, and power supply. These were examined from a R&M standpoint to provide the required avionics LCC model inputs (e.g., MTTR, MTBF, etc.), and the results are shown in Table 20. For initial spare allocation, a minimum of one contingency O-level spare per rack module and WRA module per site was assumed, with additional spare requirements based on the individual predicted MTBF and depot pipeline turnaround times. The additional costs to stock and

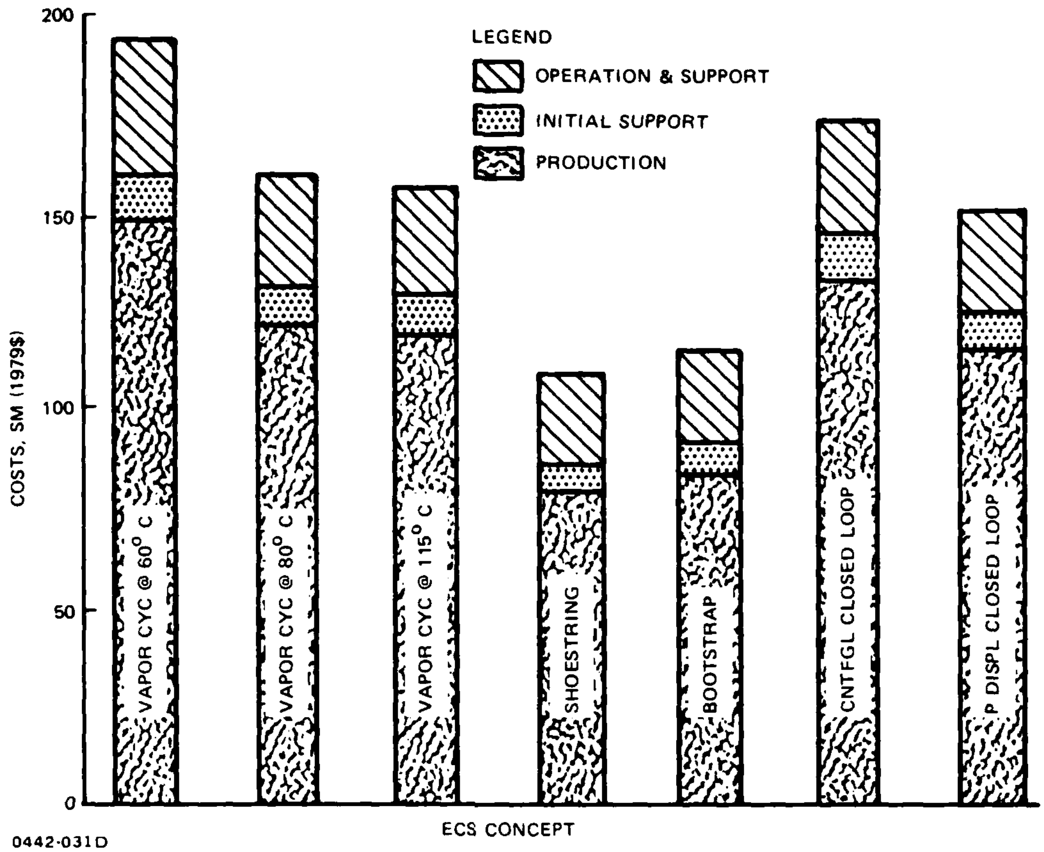

Figure 15. ECS Cost Comparison*

*R&D costs which amount to about 4% of the costs shown for each ECS concept are not included

repair lower level assemblies were considered by adding 0.1% of the total unit cost of each generic rack module type to each repair action.

The results of the avionics subsystem study alone are shown in Fig. 16. Production costs are clearly shown to be the drivers, accounting for about 90% of the LCC at a 115°C junction temperature. This temperature corresponds to a system MTBF of 8.5 hours which also accounts for a low initial support and O&S cost. Figure 16 also shows that the O&S costs do not increase significantly until the MTBF is less than 10 hours. The study further indicates that the avionics costs are relatively insensitive to junction temperatures below approximately 115°C. This is due primarily to the high reliability of the rack modules and WRAs.

Table 20 Avionic Reliability Prediction

WRA	O-LEVEL MTTR	MTBF @ JUNCTION TEMP		
		60°C	80°C	115°C
VHF/UHF RADIO SET	1.11	685	491	300
UHF RADIO SET	0.76	533	382	233
UHF CRYPTO SET	0.80	267	191	117
ICS	0.78	267	191	117
IFF TRANSPONDER	0.83	305	218	133
IFF KIT – 1A/TSEC	0.83	305	218	133
RADAR ALTIMETER	0.98	457	327	200
RADAR BEACON	0.98	1370	981	600
INTEGRATED SENSOR SYS	1.10	152	109	67
AIR DATA COMPUTER	1.0	610	436	267
DOPPLER VELOCITY SENSOR	1.10	419	300	183
ILS SET	0.80	762	545	333
UHF/ADF SET	0.76	762	545	333
GPS RCVR/PROC	0.75	533	382	233
AFCS (3)	1.04	457	327	200
RADAR ANTENNA MODULES (56)	0.75	3050	2180	1333
INTEGRATED RACK MODULES		MTBF PER MODULE		
MEMORY (142)	0.2	78,700	51,300	30,000
DIGITAL (300)	0.2	132,000	108,000	73,000
ANALOG (58)	0.2	147,000	120,000	52,400
POWER SUPPLY (333 SLOTS)	0.2	1,970,000	1,540,000	714,000
TOTAL MTBF, HR		19.4	14.0	8.5
TOTAL MTBM, HR		12.8	9.3	5.7

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4.3.3 Total Program Life Cycle Cost Differentials

Figure 17 shows program LCC differentials versus avionic component junction temperature for the various ECS concepts. It can be seen that junction temperature is a powerful cost driver. This is so because the lower temperatures require a larger ECS which results in a larger, heavier aircraft, and heavier aircraft cost more to manufacture and operate. Avionics, in the range of junction temperatures investigated (as discussed in sub-section 4.3.2) were found to be small drivers of program costs, because of the relatively high reliability of the avionics in the aircraft. The costs of the ECS itself were found to be of secondary importance. The primary program cost driver is the effect of the ECS concept on aircraft size.

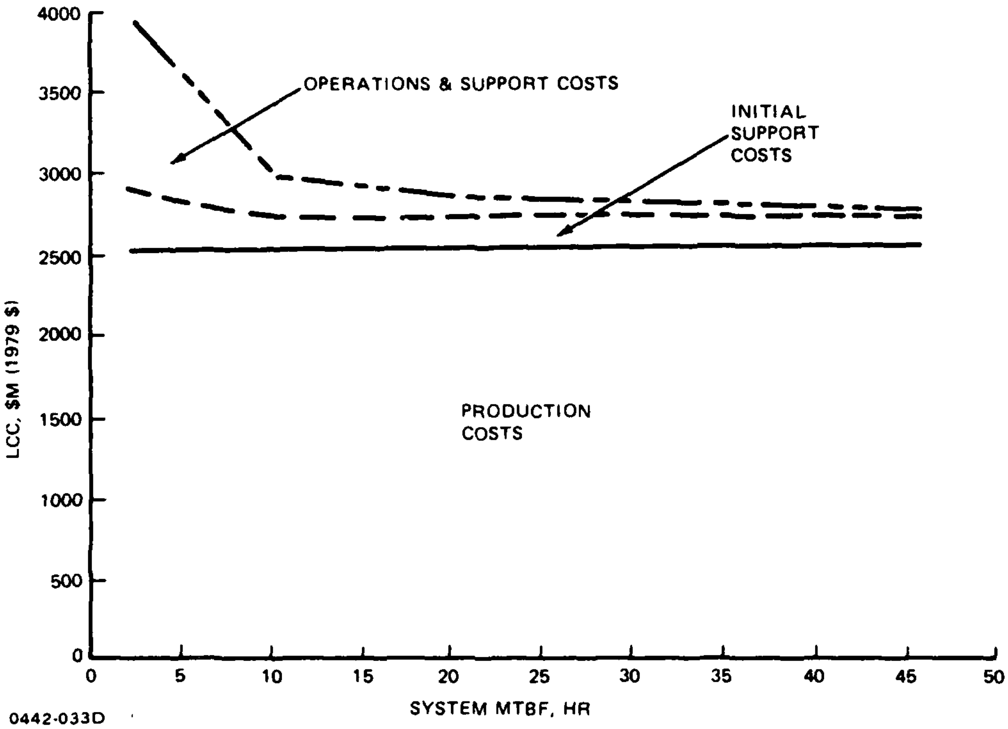

Figure 16. V/STOL Avionic LCC Sensitivity to MTBF

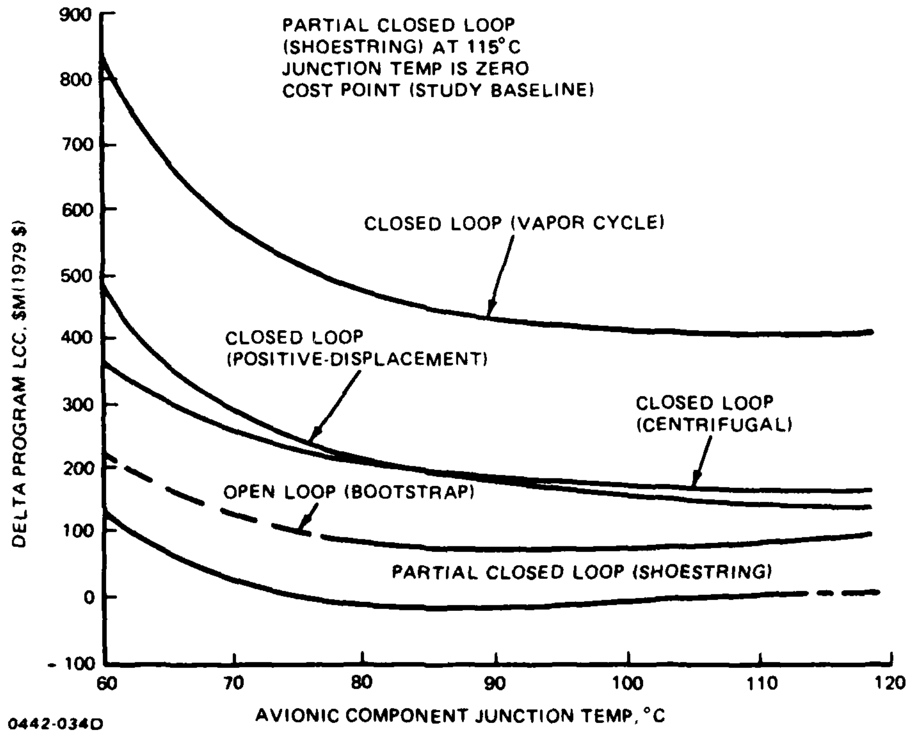

Figure 17. Program LCC Differentials

The study results show that the partially closed loop shoestring ECS, the smallest and lightest system is by far the least-expensive, while the closed-loop systems, the heaviest and most complex, are the most expensive. For all closed-loop ECS concepts, the LCCs increase with decreasing junction temperatures, whereas they are at a minimum in the 80 to 90°C temperature range for the others. The increases are most rapid at temperatures less than 80°C. This suggests a practical lower junction temperature design limit of about 80 to 90°C.

5 - CONCLUSIONS

It was found that a partially closed ECS as represented by the shoestring air cycle ECS results in both the lowest life cycle costs and the lowest penalties to the subsonic VSTOL aircraft. Such a bleed-air driven machine with its partial recirculation of cooling air was found to surpass both an open loop bootstrap air cycle and a fully closed loop ECS (as represented by a vapor cycle, or a closed centrifugal air cycle or positive displacement air cycle). In addition it was found to offer a high reliability at a reasonable design risk, something that the closed loop ECS concepts could not nearly begin to duplicate. The closed loop ECS concepts were found to have the highest LCC, highest aircraft penalties, highest development risk and the lowest reliabilities.

In addition it was discovered that in the range of avionics junction temperatures between 60°C and 115°C, the 80°C to 90°C junction temperature is near optimum from a life cycle cost standpoint for the shoestring air cycle ECS. From an aircraft penalty standpoint, however, the penalties are slightly lower at 115°C.

6 - RECOMMENDATIONS

Because the study results are affected to a great degree by aircraft mission profile and aircraft design, it is recommended that the existing study be extended to:

- Include several partially closed ECS concepts. For example, a recirculating bootstrap air cycle or a recirculating three-wheel air cycle could serve as the nucleus of a partially closed ECS. In this manner the optimum system concept could be identified
- Determine the LCC and the aircraft penalties associated with different ratios of WRA to rack-mounted avionics. Since this ratio affects the sizing of the ECS and thus its penalties, it is suggested that it be made a study variable so that the optimum mix can be determined for subsonic V/STOL aircraft.

In addition to the above study extensions it is recommended that a study similar to the one just conducted be done for a supersonic fighter V/STOL aircraft. In this way all the AEW/ASW and fighter aircraft V/STOL concepts will be covered.

7 - REFERENCES

1. Grumman Aerospace Corp., **Proposal for Lightweight ECS Concept Study for Type A V/STOL Aircraft**, March, 1978.

2. **Design 698 Type "A" V/STOL Weapon System**, Grumman Aerospace Corp., May 1977

3. **Nonelectronic Reliability Notebook**, RADC-TR-75-22, Rome Air Development Center

4. **Evaluation of Environmental Profiles for Reliability Demonstration**, RADC Report Nr. TR-75-242, Grumman Aerospace Corp.

APPENDIX A - PRELIMINARY ECS SCHEMATICS AND RESULTS

On the following pages, the results of the preliminary investigations, referred to in Section 3.1, are shown. ECS schematics, performance, and penalties are presented for each of the concepts examined. Of those examined, only five were carried over into the final, detailed investigations discussed in Section 3.2.

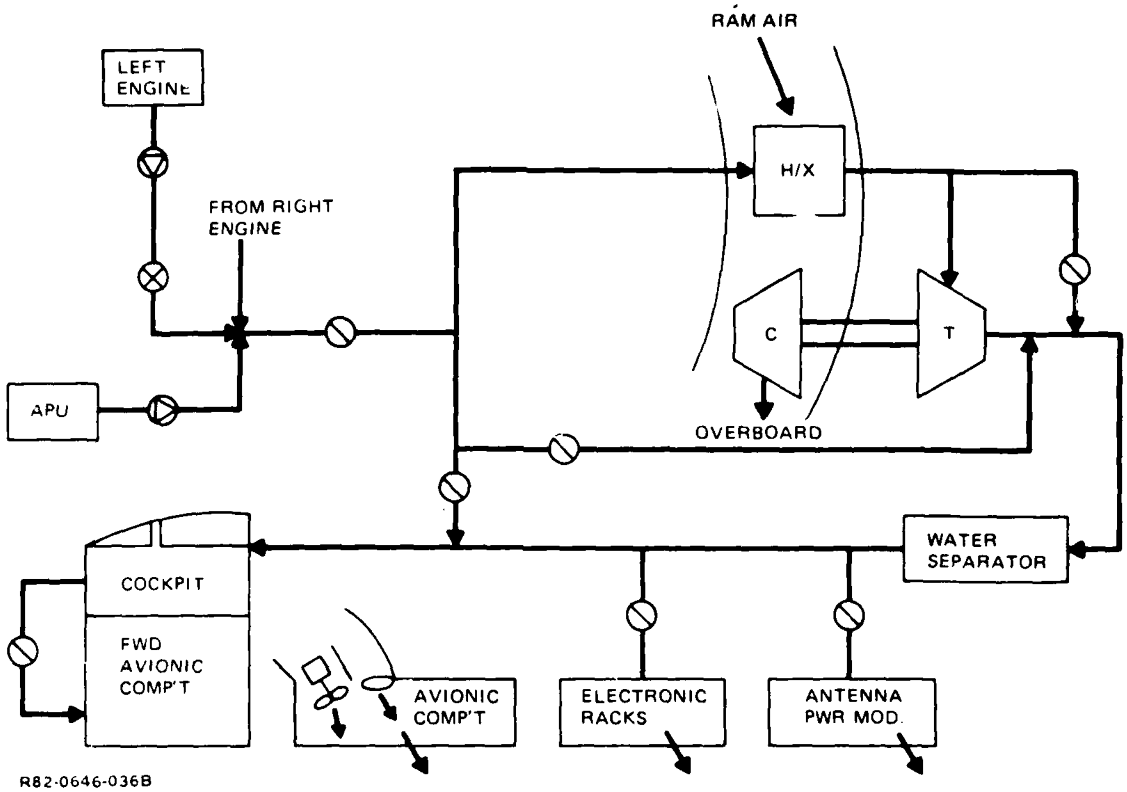

Figure A-1. Simple Air Cycle System

Table A-1 Simple Cycle – Weight Summary

HEAT EXCHANGERS	61.0
TURBINE	35.0
FANS	–
WATER SEPARATOR	19.1
SCOOPS	13.6
DUCTING	148.0
VALVES	42.4
PLUMBING	20.0
INSULATION	15.7
CONTROLS	23.0
INSTALLATION	78.15
TOTALS	456.0

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Table A-2 Simple Air Cycle – TOGW Penalties

MISSION SEGMENT	VEHICLE PENALTY: WEIGHT LBS	VEHICLE PENALTY: TOGW PENALTY LBS	BLEED PENALTY: BLEED FLOW LBS/MIN	BLEED PENALTY: TOGW PENALTY LBS	POWER PENALTY: SHP EXTRACTED HP	POWER PENALTY: TOGW PENALTY LBS	RAM PENALTY: RAM FLOW LB/MIN	RAM PENALTY: TOGW PENALTY LBS
TAKE-OFF			89.3	262.5	0	0	170.0	0
IRT CLIMB			67.8	51.5			155.0	18.6
CRUISE OUT & BACK	456.0	1824.0	65.0	123.5			106.0	11.66
LOITER @ ALTITUDE			65.0	780.0			100.0	42.2
S.L. LOITER			89.3	145.0	0	0	210.0	14.7
SUB-TOTALS	456.0	1824.0	–	1367.5	–	–	–	87.16
0442-036D	TOTAL TOGW PENALTY 3278.66 LBS.							

Table A-3 Simple Air Cycle (Cooling Cabin & Antenna Pwr Modules) – TOGW Penalties

MISSION SEGMENT	VEHICLE PENALTY: WEIGHT LBS	VEHICLE PENALTY: TOGW PENALTY LBS	BLEED PENALTY: BLEED FLOW LBS/MIN	BLEED PENALTY: TOGW PENALTY LBS	POWER PENALTY: SHP EXTRACTED HP	POWER PENALTY: TOGW PENALTY LBS	RAM PENALTY: RAM FLOW LB/MIN	RAM PENALTY: TOGW PENALTY LBS
TAKE-OFF			50.0	147.0	0	0	–	0
IRT CLIMB			73.8	56.1			81.2	9.7
CRUISE OUT & BACK	368.4	1473.6	27.5	52.3			42.4	4.7
LOITER @ ALTITUDE			27.5	330.0			42.4	17.8
S.L. LOITER			50.0	81.5	0	0	120.0	8.4
SUB-TOTALS	368.4	1473.6	–	666.9		0	–	40.6
0442-037D	TOTAL TOGW PENALTY 2181.1 LBS.							

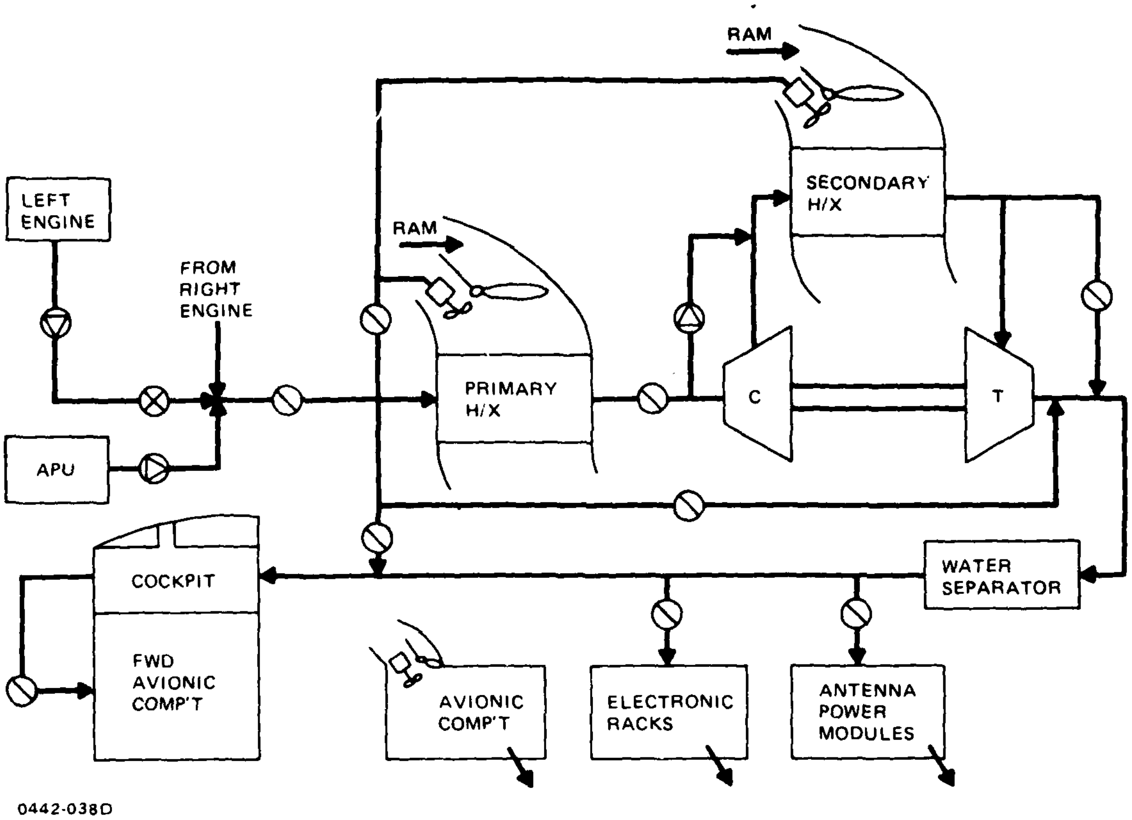

Figure A-2. Bootstrap System

Table A-4 Bootstrap – Weight Summary

HEAT EXCHANGERS	124.6
TURBINE	25.0
FANS	15.0
WATER SEPARATOR	19.1
SCOOPS	23.6
DUCTING	162.0
VALVES	45.4
PLUMBING	20.0
INSULATION	15.7
CONTROLS	23.0
INSTALLATION	95.1
TOTALS	568.5 LBS

0442-039D

Table A-5 Bootstrap Air Cycle – TOGW Penalties

MISSION SEGMENT	VEHICLE PENALTY		BLEED PENALTY		POWER PENALTY		RAM PENALTY	
	WEIGHT LBS	TOGW PENALTY LBS	BLEED FLOW LBS/MIN	TOGW PENALTY LBS	SHP EXTRACTED HP	TOGW PENALTY LBS	RAM FLOW LB/MIN	TOGW PENALTY LBS
TAKE-OFF	568.5	2274.0	101.3	297.8	0	0	160.0	0
IRT CLIMB			67.8	51.5			108.5	13.0
CRUISE OUT & BACK			65.0	123.5			145.0	16.0
LOITER @ ALTITUDE			65.0	780.0			115.0	48.3
S.L. LOITER			89.3	145.5	0	0	102.0	7.1
SUB-TOTALS	568.5	2274.0	–	1398.3	0	0		84.4

0442-040D TOTAL TOGW PENALTY 3756.7 LBS.

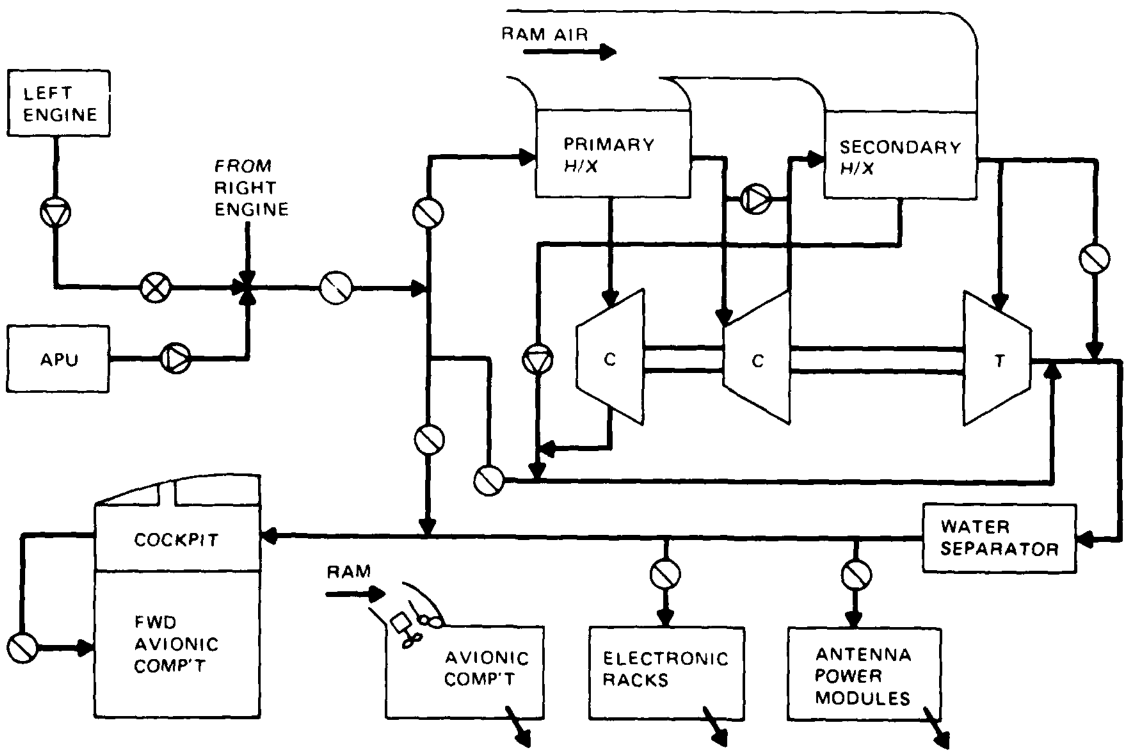

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Figure A-3. 3-Wheel Bootstrap System

Table A-6 3-Wheel Bootstrap – Weight Summary

HEAT EXCHANGERS	124.6
TURBINE	35.0
FANS	–
WATER SEPARATOR	19.1
SCOOPS	20.0
DUCTING	162.0
VALVES	43.6
PLUMBING	20.0
INSULATION	15.7
CONTROLS	23.0
INSTALLATION	94.1
TOTALS	557.1 LBS

0442-042D

Table A-7 3-Wheel Bootstrap – TOGW Penalties

MISSION SEGMENT	VEHICLE PENALTY		BLEED PENALTY		POWER PENALTY		RAM PENALTY	
	WEIGHT LBS	TOGW PENALTY LBS	BLEED FLOW LBS/MIN	TOGW PENALTY LBS	SHP EXTRACTED HP	TOGW PENALTY LBS	RAM FLOW LB/MIN	TOGW PENALTY LBS
TAKE-OFF			89.3	262.5	0	0	109.0	–
IRT CLIMB			67.8	51.5			112.8	13.5
CRUISE OUT & BACK	557.1	2228.4	65.0	123.5			150.8	16.5
LOITER @ ALTITUDE			65.0	780.0			115.0	48.3
S.L. LOITER			89.3	145.5	0	0	106.0	7.4
SUB-TOTALS	557.1	2228.4	–	1363.0	–	0	–	85.8

TOTAL TOGW PENALTY 3677.2 LBS.

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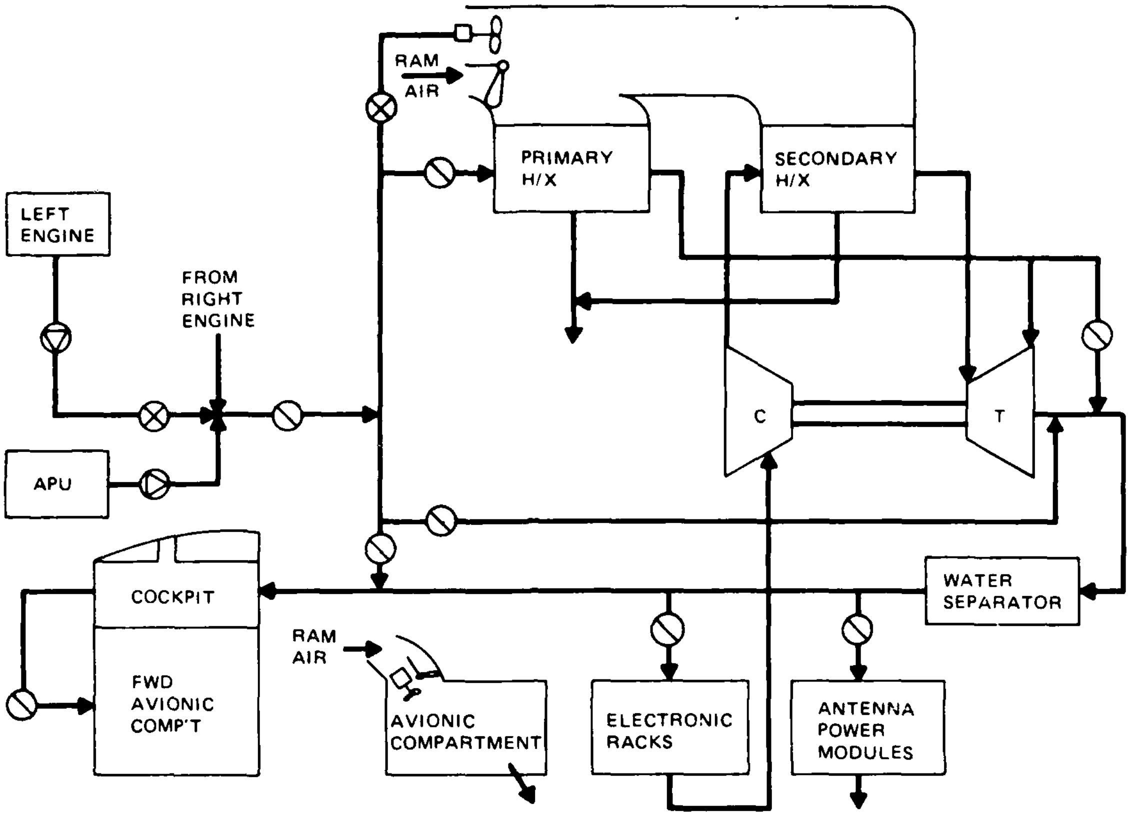

Figure A-4. Shoestring System

Table A-8 Shoestring Cycle – Weight Summary

HEAT EXCHANGERS	116.0
TURBINE	30.0
FANS	15.0
WATER SEPARATOR	19.1
SCOOPS	13.6
DUCTING	177.0
VALVES	45.4
PLUMBING	20.0
INSULATION	16.3
CONTROLS	23.0
INSTALLATION	111.0
TOTALS	586.4 LBS

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Table A-9 Shoestring Air Cycle – TOGW Penalties

MISSION SEGMENT	VEHICLE PENALTY		BLEED PENALTY		POWER PENALTY		RAM PENALTY	
	WEIGHT LBS	TOGW PENALTY LBS	BLEED FLOW LBS/MIN	TOGW PENALTY LBS	SHP EXTRACTED HP	TOGW PENALTY LBS	RAM FLOW LB/MIN	TOGW PENALTY LBS
TAKE-OFF			58.2	171.1	0	0	280.5	
IRT CLIMB			46.2	35.1			231.0	27.7
CRUISE OUT & BACK	586.4	2345.6	34.2	65.0			202.0	22.2
LOITER @ ALTITUDE			34.2	410.0			168.0	70.76
S.L. LOITER			58.2	94.8	0	0	218.0	15.3
SUB-TOTALS		2345.6		776.0	0	0		135.76
0442-046D	TOTAL TOGW PENALTY 3257.4 LBS.							

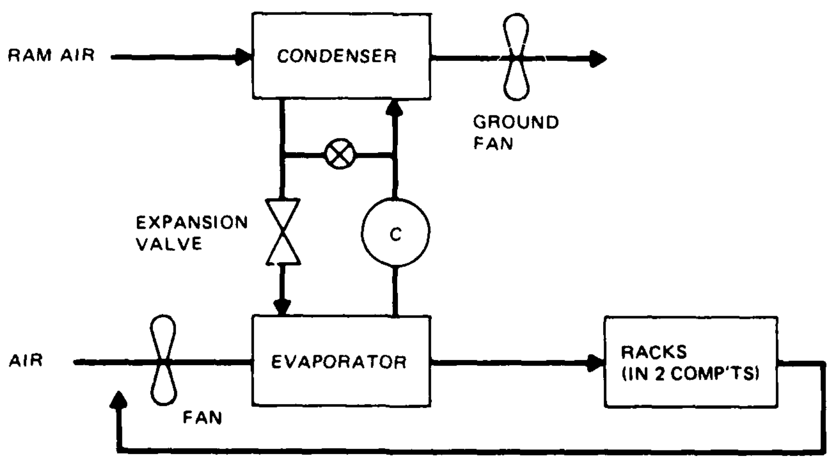

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Figure A-5. Vapor Cycle/Air Cooled Racks System

Table A-10 Vapor Cycle Cooling of Racks (Air Distr) — Weight Summary

CONDENSER	39.2
EVAPORATOR	16.1
COMPRESSOR	18.6
REFRIGERANT	11.1
CONDENSER FAN	22.3
SENSORS, SWITCHES, VALVES	14.9
CONDENSOR SCOOP	48.4
CABLES AND PLUGS	16.6
INSTALLATION HARDWARE	42.8
DISTR DUCTING, COUPLINGS, RAM AIR HARDWARE	44.5
FAN & MOUNTING	52.8
TOTALS	327.3

0442-048D

Table A-11 Vapor Cycle for Racks (Air Distribution) — Weight Summary

MISSION SEGMENT	VEHICLE PENALTY		BLEED PENALTY		POWER PENALTY		RAM PENALTY	
	WEIGHT LBS	TOGW PENALTY LBS	BLEED FLOW LBS/MIN	TOGW PENALTY LBS	SHP EXTRACTED HP	TOGW PENALTY LBS	RAM FLOW LB/MIN	TOGW PENALTY LBS
TAKE-OFF	327.3	1309.2	0	0	20.0	2.5	–	0
IRT CLIMB					20.5	5.4	67.7	8.1
CRUISE OUT & BACK					21.1	8.7	37.4	4.1
LOITER @ ALTITUDE					21.2	46.4	37.4	15.7
S.L. LOITER			0	0	20.0	10.8	135.4	9.5
SUB-TOTALS	327.3	1309.2	0	0	–	73.8	–	37.4

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TOTAL TOGW PENALTY 1420.4 LBS.

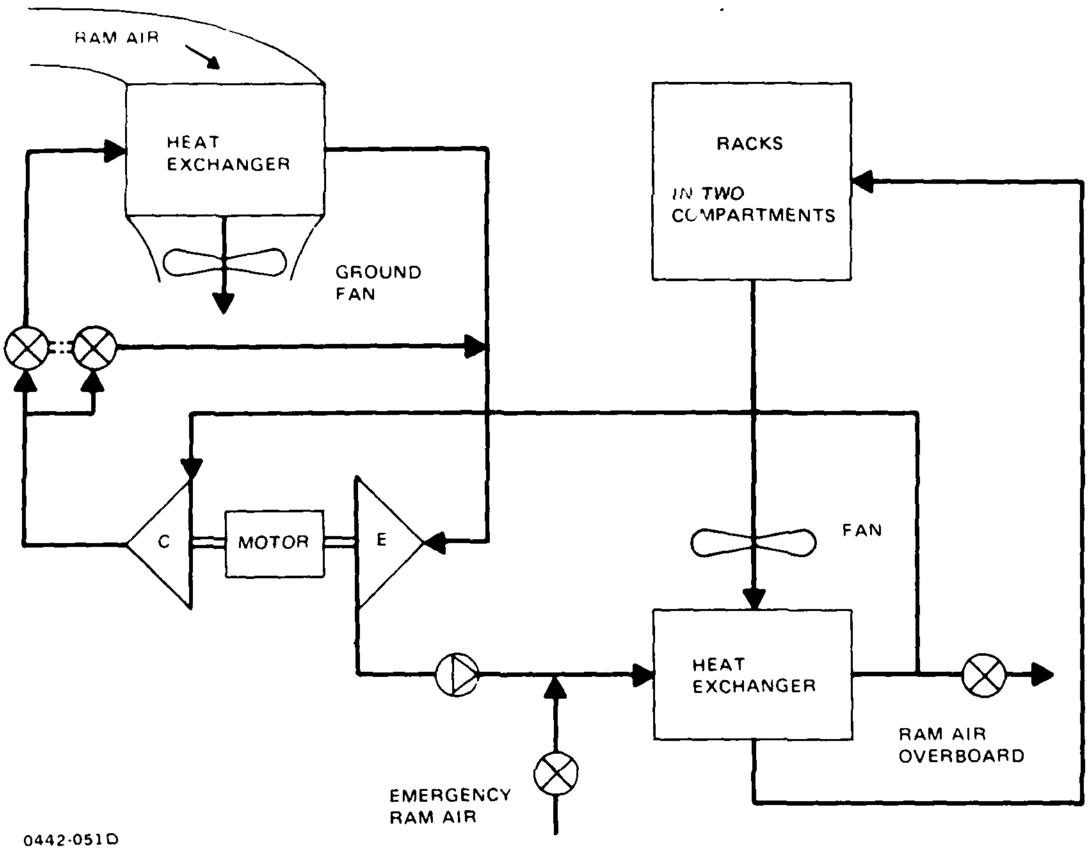

Figure A-6. Positive Displacement Air Cycle Machine For Rack Cooling - System

Table A-12 Positive Displacement ACM – Weight Summary

HEAT EXCHANGER	30.0
POSITIVE DISPLACEMENT ACM	43.2
HYDRAULIC MOTOR	17.8
HYDRAULIC VALVE CONTROLS & LINES	10.5
DUCTING	93.3
VALVES	24.8
INSULATION	18.1
SCOOPS	13.0
FAN	12.0
INSTALLATION	81.3
TOTALS	344.0

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Table A-13 Positive Displacement ACM for Rack Cooling Only – TOGW Penalties

MISSION SEGMENT	VEHICLE PENALTY: WEIGHT LBS	VEHICLE PENALTY: TOGW PENALTY LBS	BLEED PENALTY: BLEED FLOW LBS/MIN	BLEED PENALTY: TOGW PENALTY LBS	POWER PENALTY: SHP EXTRACTED HP	POWER PENALTY: TOGW PENALTY LBS	RAM PENALTY: RAM FLOW LB/MIN	RAM PENALTY: TOGW PENALTY LBS
TAKE OFF	344.0	1376.0	0	0	44.4	5.5	100.0	-
IRT CLIMB						11.7	75.0	9.0
CRUISE OUT & BACK						18.2	35.0	3.8
LOITER @ ALTITUDE						97.7	30.0	12.6
S.L. LOITER			0	0	44.4	24.0	90.0	6.3
SUB TOTALS	344.0	1376.0	0	0	-	157.1	-	31.7

TOTAL TOGW PENALTY 1564.8 LBS.

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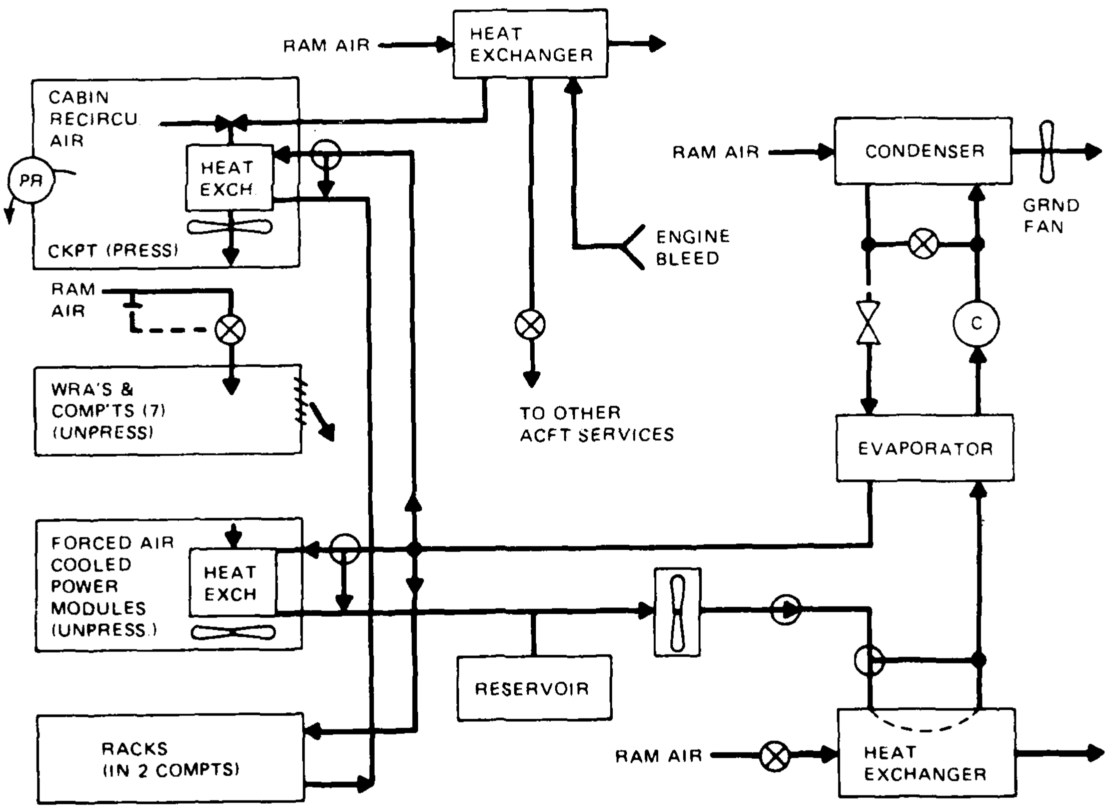

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Figure A-7. Single Vapor Cycle - System

Table A-14 Single Vapor Cycle System – Weight Summary

• VAPOR CYCLE SYSTEM	
CONDENSER	74.0
EVAPORATOR	30.5
COMPRESSOR	35.0
REFRIGERANT	21.0
CONDENSER FAN	42.0
SENSORS, SWITCHES, VALVES	28.1
CONDENSER SCOOP	91.4
CABLE & PLUGS	31.4
INSTALLATION HARDWARE	80.1
• LIQUID COOLING LOOP	
HEAT EXCHANGERS	70.0
FANS	48.0
COOLANT	79.8
TUBING & COUPLING	51.2
VALVES, TANK, PUMPS	26.3
INSTALLATION HARDWARE	39.3
• BLEED HARDWARE	
PRE-COOLER & SCOOP	12.8
VALVES, SENSORS, BLEED DUCTS	11.2
TOTALS	772.1

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Table A-15 Single Vapor Cycle System – TOGW Penalties

MISSION SEGMENT	VEHICLE PENALTY		BLEED PENALTY		POWER PENALTY		RAM PENALTY	
	WEIGHT LBS	TOGW PENALTY LBS	BLEED FLOW LBS/MIN	TOGW PENALTY LBS	SHP EXTRACTED HP	TOGW PENALTY LBS	RAM FLOW LB/MIN	TOGW PENALTY LBS
TAKE OFF	772.1	3088.4	3.6	4.75	45.0	5.5	0	0
IRT CLIMB			4.6	1.56	45.5	12.0	141.0	16.9
CRUISE OUT & BACK			5.6	10.6	46.0	18.9	72.9	8.6
LOITER @ ALTITUDE			5.6	30.2	46.0	101.2	77.9	32.7
S.L. LOITER			3.6	2.7	45.0	24.3	282.0	19.7
SUB-TOTALS	772.1	3088.4	–	49.8	–	161.9	–	77.9

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TOTAL TOGW PENALTY 3378.0 LBS.

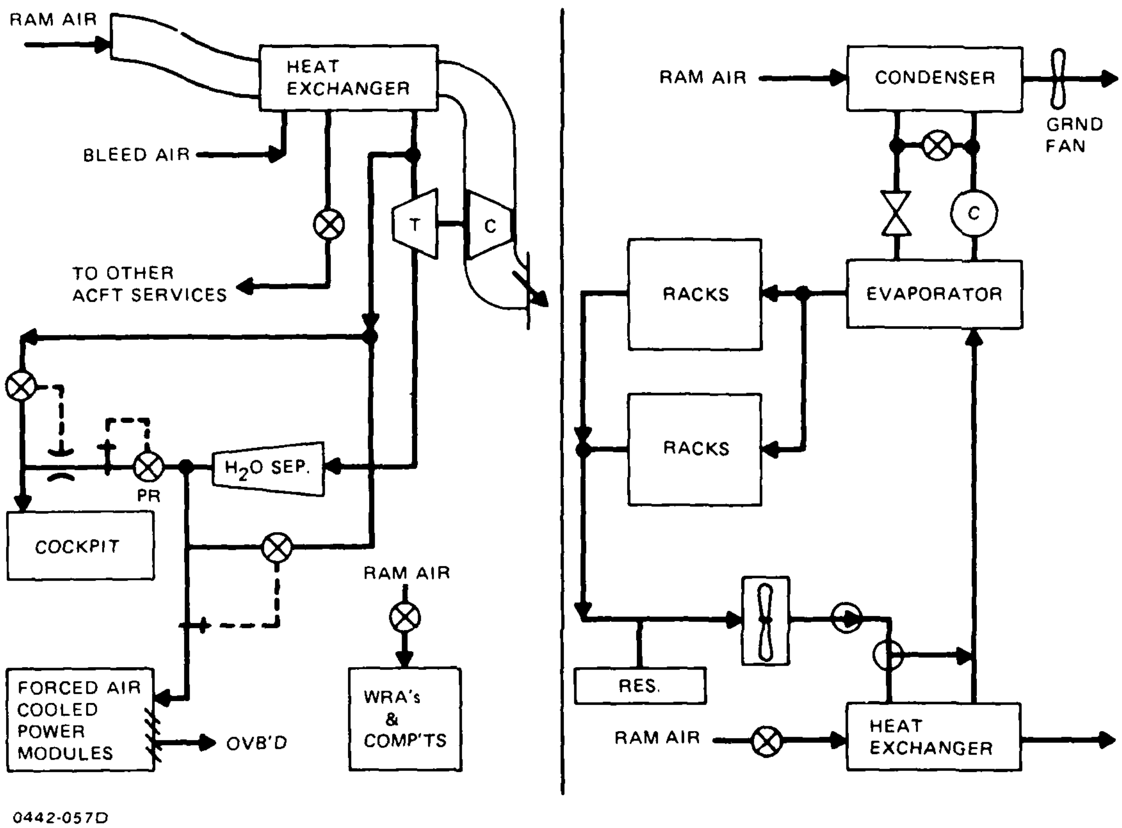

Figure A-8. Simple Air Cycle W/Vapor Cycle Liq Cooled Racks

Table A-16 Simple Air Cycle with Vapor Cycle Cooling of Racks (Air Distribution) – Weight Summary

• AIR CYCLE SYSTEM	
HEAT EXCHANGERS	54.1
TURBINE-COMPRESSOR	30.0
FANS	
WATER SEPARATOR	17.5
SCOOPS	13.0
DUCTING	112.2
VALVES	31.4
PLUMBING	18.0
INSULATION	13.8
CONTROLS	23.0
INSTALLATION	55.4
SUB-TOTALS	368.4
• VAPOR CYCLE & AIR DISTR	
CONDENSOR	39.2
EVAPORATOR	16.1
COMPRESSOR	18.6
REFRIGERANT	11.1
CONDENSER FAN	22.3
SENSORS, SWITCHES, VALVES	14.9
CONDENSER SCOOP	48.4
CABLE & PLUGS	16.6
INSTALLATION HARDWARE	42.8
DIST. DUCTS	44.5
FAN & MOUNTING	52.8
SUB-TOTAL	327.3
TOTAL	695.7

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Table A-17 Simple Air Cycle with Vapor Cycle Cooling of Racks (Liquid Heat Transport System) – TOGW Penalties

MISSION SEGMENT	VEHICLE PENALTY WEIGHT LBS	VEHICLE PENALTY TOGW PENALTY LBS	BLEED PENALTY BLEED FLOW LBS/MIN	BLEED PENALTY TOGW PENALTY LBS	POWER PENALTY SHP EXTRACTED HP	POWER PENALTY TOGW PENALTY LBS	RAM PENALTY RAM FLOW LB/MIN	RAM PENALTY TOGW PENALTY LBS
TAKE-OFF	692.7	2770.8	50.0	147.0	17.7	2.2	-	0
IRT CLIMB			73.8	56.1	18.2	4.8	142.3	17.0
CRUISE OUT & BACK			27.5	52.3	18.6	7.6	76.2	8.4
LOITER @ ALTITUDE			27.5	330.0	18.6	40.9	76.2	32.0
S.L. LOITER			50.0	81.5	17.7	9.6	242.3	17.0
SUB-TOTALS	692.7	2770.8	-	666.9	-	65.1	-	74.4

TOTAL TOGW PENALTY 3577.2 LBS.

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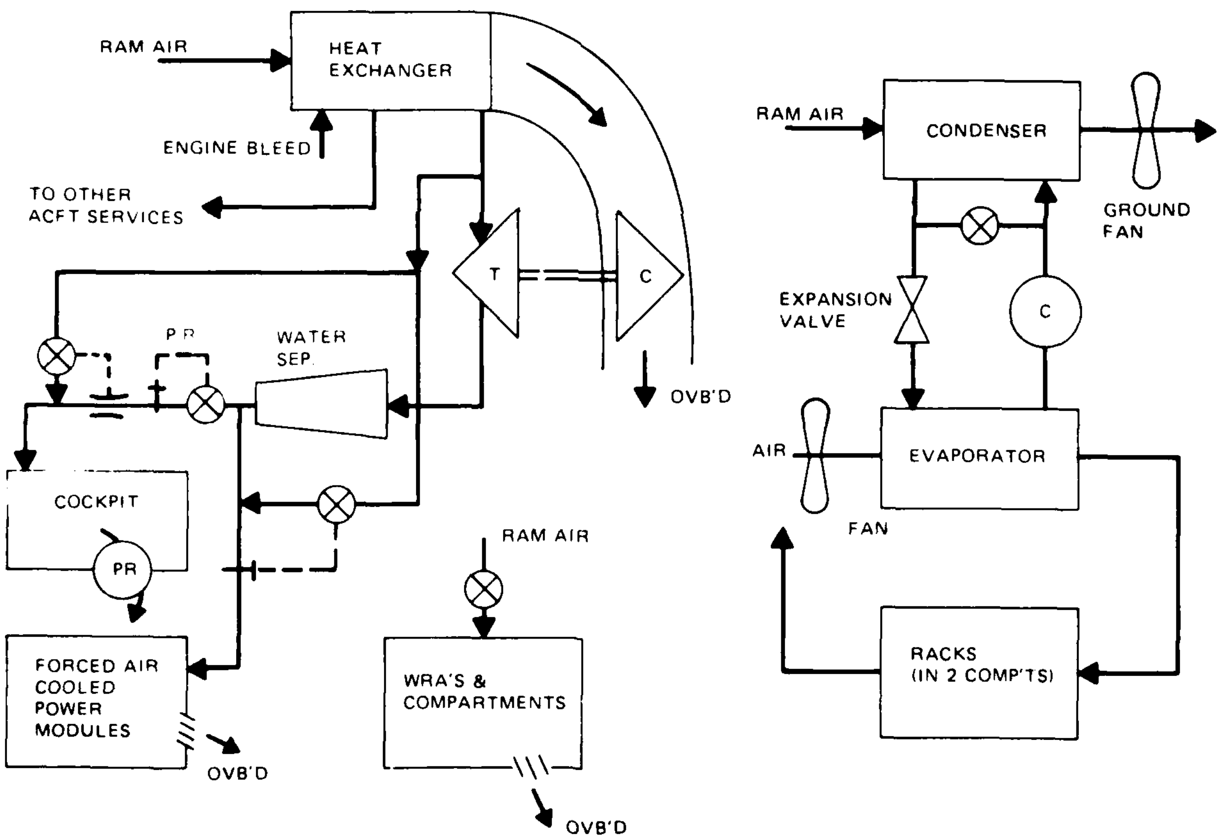

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Figure A-9. Simple Air Cycle With Vapor Cycle/Air Cooled Racks - System

Table A-18 Simple Air Cycle with Vapor Cooled Racks (Liquid Distribution Loop) — Weight Summary

• AIR CYCLE SYSTEM	
HEAT EXCHANGERS	54.1
TURBO-COMPRESSOR	30.0
WATER SEPARATOR	17.5
SCOOPS	13.0
DUCTING	112.2
INSULATION	13.8
VALVES	31.4
DUCTING, COUPLINGS	18.0
CONTROLS	23.0
INSTALLATION	55.4
• VAPOR CYCLE SYSTEM	
CONDENSER	37.6
EVAPORATOR	13.8
COMPRESSOR	17.1
REFRIGERANT	10.9
CONDENSER FAN	21.6
SENSORS, SWITCHES, VALVES	14.9
CONDENSER SCOOP	47.6
CABLES & PLUGS	16.6
INSTALLATION	41.7
• LIQUID DISTRIBUTION LOOP	
HEAT EXCHANGER (RAM)	19.8
COOLANT	23.6
TUBING & COUPLINGS	21.4
VALVES, TANKS & PUMPS	20.5
INSTALLATION HD'WRE	17.2
TOTAL	692.7 LBS

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Table A-19 Simple Air Cycle with Vapor Cycle for Racks – TOGW Penalties

MISSION SEGMENT	VEHICLE PENALTY: WEIGHT LBS	VEHICLE PENALTY: TOGW PENALTY LBS	BLEED PENALTY: BLEED FLOW LBS/MIN	BLEED PENALTY: TOGW PENALTY LBS	POWER PENALTY: SHP EXTRACTED HP	POWER PENALTY: TOGW PENALTY LBS	RAM PENALTY: RAM FLOW LB/MIN	RAM PENALTY: TOGW PENALTY LBS
TAKE-OFF	695.7	2782.8	50.0	147.0	20.0	2.5	–	0
IRT CLIMB			73.8	56.1	20.5	5.4	148.9	17.8
CRUISE OUT & BACK			27.5	52.3	21.1	8.7	79.8	8.8
LOITER @ ALTITUDE			27.5	330.0	21.1	46.4	79.8	33.5
S.L. LOITER			50.0	81.5	20.0	10.8	255.4	17.9
SUB-TOTALS	695.7	2782.8	–	666.9	–	73.8	–	78.0
TOTAL TOGW PENALTY 3601.5 LBS.								

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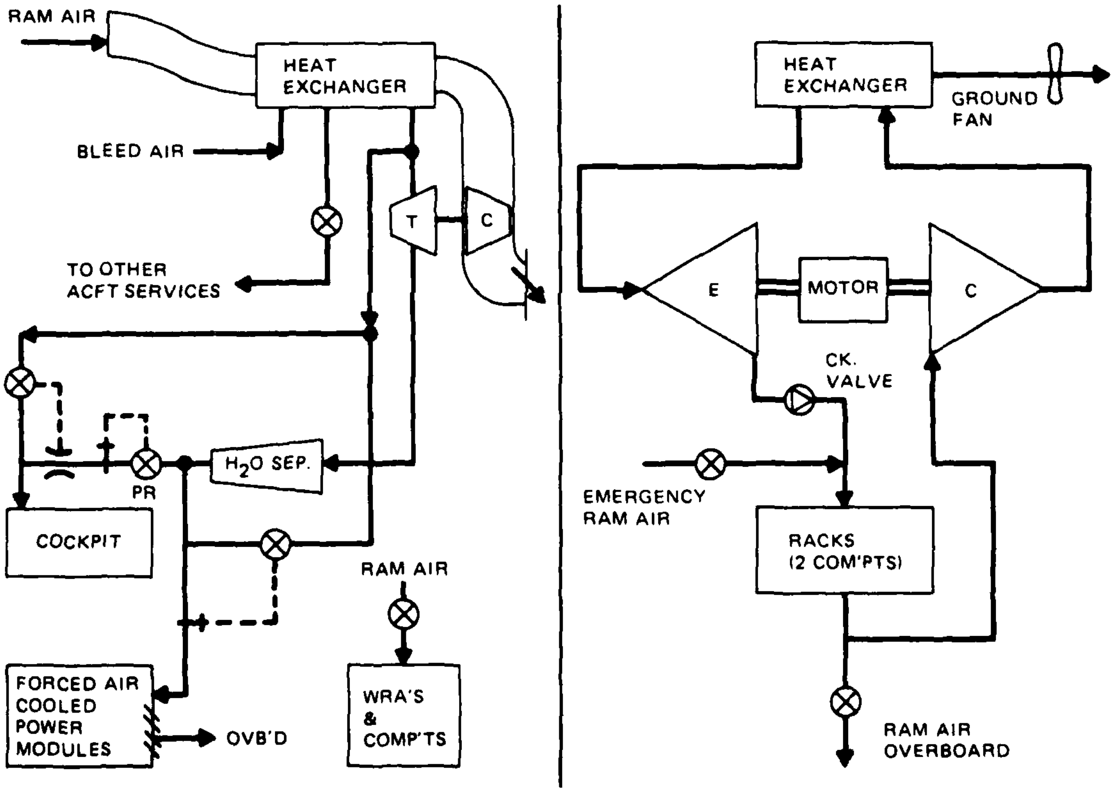

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Figure A-10. Simple Air Cycle W/Positive Displacement Cooled Racks

Table A-20 Simple Air Cycle with Positive Displacement Cooled Racks - TOGW Penalties

MISSION SEGMENT	WEIGHT PENALTY: WEIGHT LBS	WEIGHT PENALTY: TOGW PENALTY LBS	BLEED PENALTY: BLEED FLOW LBS/MIN	BLEED PENALTY: TOGW PENALTY LBS	POWER PENALTY: SHP EXTRACTED HP	POWER PENALTY: TOGW PENALTY LBS	RAM PENALTY: RAM FLOW LB/MIN	RAM PENALTY: TOGW PENALTY LBS
TAKE-OFF	712.4	2849.0	50.0	147.0	44.4	5.5	100.0	–
IRT CLIMB			73.8	56.1		11.7	156.2	18.7
CRUISE OUT & BACK			27.5	52.3		18.2	77.4	8.5
LOITER @ ALTITUDE			27.5	330.0		97.7	72.4	30.4
S.L. LOITER			50.0	81.5	44.4	24.0	210.0	14.7
SUB-TOTALS	712.4	2849.0	–	666.9	–	157.1	-	72.3
TOTAL TOGW PENALTY 3745.3 LBS.								

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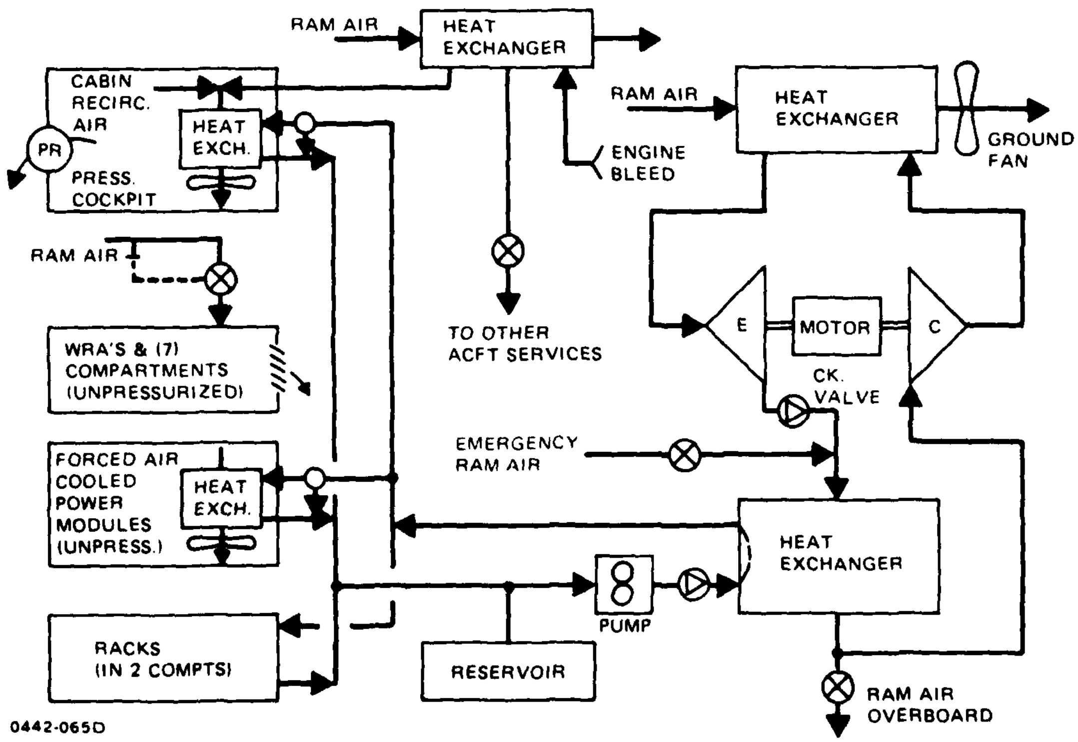

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Figure A-11. Single Positive Displacement Air Cycle Machine

APPENDIX B - ECS RELIABILITY/MAINTAINABILITY STUDY RESULTS

The component failure-rate data and meantime-to-repair data used to assess ECS system reliability and maintainability characteristics for the five ECS concepts examined in detail is given on the following page. Overall system characteristics are discussed in Section 3.2.2.

Table B-1 V/STOL ECS R&M Assessment

COMPONENT	FAIL RATE (λ)	MTTR (R)	VAPOR CYCLE 60°C (N) QUANT	60°C Nλ	60°C NλR	80°C (N) QUANT	80°C Nλ	80°C NλR	115°C (N) QUANT	115°C Nλ	115°C NλR
1 FREON CONDENSER	3	2.4	2	6	14.4	1	3	7.2	1	3	7.2
2 FREON CONTROLLER	158	1.2	2	316	379.2	1	158	189.6	1	158	189.6
3 COOLANOL FREON EVAPORATOR	3	2.4	2	6	14.4	1	3	7.2	1	3	7.2
4 FREON COMPRESSOR	282	1.3	2	564	733.2	1	282	366.6	1	282	366.6
5 [illegible] EXP VALVE	80	1.0	2	160	160	1	80	80	1	80	80
6 ORIFICE	3	0.8	6	18	14.4	3	9	7.2	3	9	7.2
7 AIR SCOOP EXT ACTUATOR	204	1.5	1	204	306	1	204	306	1	204	306
8 FREON TUBING & FITTINGS	2	1.0	50	100	100	50	100	100	50	100	100
9 FREON RECEIVER	50	1.4	2	100	140	1	50	70	1	50	70
10 CONTROL VALVE POSITIONER	19	0.6	2	38	22.8	1	19	11.4	1	19	11.4
11 [illegible] THROTTLE VALVE	80	1.0	2	160	160	1	80	80	1	80	80
12 PRESSURE SENSOR	95	0.6	4	380	228	2	190	114	2	190	190
13 PRESS RELIEF VALVE	31	1.2	2	62	74.4	1	31	37.2	1	31	37.2
14 RAM AIR HEAT EXCHANGER	3	2.0	17	51	102	17	51	102	17	51	102
15 RAM AIR HEAT EXCHANGER	3	2.4	2	6	14.4	2	6	14.4	1	3	7.2
16 RAM AIR SHUTOFF VALVE	70	0.7	2	140	98	2	140	98	1	70	49
17 COOLANOL PUMP	134	1.2	2	268	321.6	1	134	160.8	1	134	160.8
18 COOLANOL RESERVOIR	50	1.0	2	100	100	1	50	50	1	50	50
19 TEMP CONT VALVE	80	1.3	14	1120	1456	13	1040	1352	13	1040	1352
20 TEMP CONT VALVE BAR BIAS	120	1.4	12	1440	2016	13	1452	2038.8	12	1440	2016
21 TEMP SENSOR	25	0.9	27	675	607.5	27	675	607.5	26	650	585
22 TEMP CONTROLLER	62	1.0	4	248	248	4	248	248	4	248	248
23 BLEED [illegible] VALVE	5	1.2	2	10	12	1	5	6	1	5	6
24 CHECK VALVE	13	1.0	2	26	26	1	13	13	1	13	13
25 COOLANOL TUBING & COUPLING	2	1.0	50	100	100	50	100	100	50	100	100
26 PRESS RE ALTITUDE SWITCH	56	0.8	1	56	44.8	1	56	44.8	1	56	44.8
27 [illegible]	1	0.6	1	1	0.6	1	1	0.6	1	1	0.6
28 BLEED RAM AIR HT EXCH	3	2.4	1	3	7.2	1	3	7.2	1	3	7.2
29 [illegible] PRESSURE REG	116	1.2	3	348	417.6	3	348	417.6	[illegible]	348	417.6
30 [illegible]	71	0.6	17	1207	724.2	17	1207	724.2	17	1207	724.2
31 [illegible] CONTROL	36	0.6	17	612	367.2	17	612	367.2	17	612	367.2
32 FAN SINGLE SPEED ELECT	71	1.0	1	71	71	1	71	71	1	71	71
33 FAN SINGLE SPEED PNEU	71	1.2									
34 TURBINE COMP FAN ASSY	246	1.2									
35 [illegible] HEAT EXCH	1	2.4									
36 [illegible] REHEAT EXCH	1	2.4									
37 RAM AIR HEAT EXCH	3	2.0									
38 TURBINE COMPRESSOR	150	1.6									
39 TURBINE COMP [illegible]	157	1.3									
40 [illegible] COMP ELECTRONICS	150	0.8									
41 [illegible] CONTROLLER	62	0.8									
42 COMP EXPANDER ASSY	250	1.4									
43 [illegible]	25	[illegible]									
44 [illegible]	100	0.8									
45 [illegible] VALVE	25	1.0									
46 WATER SEPARATOR	30	1.2									
47 [illegible]	30	1.4	2	60	84	1	30	42	1	30	42
48 [illegible]	26	0.6	2	52	31.2	1	26	15.6	1	26	15.6
49 DEHYDRATOR AIR	10	1.0									
50 CAB [illegible]	116	0.8	1	116	92.8	1	116	92.8	1	116	92.8
51 CAB [illegible] VALVE	31	1.0	1	31	31	1	31	31	1	31	31
52 BLEED AIR [illegible]	1	1.2	10	10	12	10	10	12	10	10	12
53 AIR [illegible]	1	1.2	10	10	12	10	10	12	10	10	12
54 COCKPIT TEMP SELECTOR	8	0.6	1	8	4.8	1	8	4.8	1	8	4.8
TOTAL				8888.8	9354.[illegible]		7631	7694.[illegible]		7642	7999.6
MTBF				112HR			131HR			131HR	
MTTR					1.05			1.05			1.05

COMPONENT	SHOESTRING (N) QUANT	SHOESTRING N	SHOESTRING N R	BOOTSTRAP (N) QUANT	BOOTSTRAP N	BOOTSTRAP N R	CLOS CYCLE CENT (N) QUANT	CLOS CYCLE CENT N	CLOS CYCLE CENT N R	CLOS CYCLE POS DIS (N) QUANT	CLOS CYCLE POS DIS N	CLOS CYCLE POS DIS N R
6 ORIFICE	10	10	24	10	10	24	[illegible]	[illegible]	[illegible]	[illegible]	10	24
13 PRESS RELIEF VALVE							[illegible]	62	74.4	[illegible]	62	74.4
14 RAM AIR HEAT EXCHANGER							[illegible]	[illegible]	102	[illegible]	[illegible]	102
16 RAM AIR SHUTOFF VALVE	5	350	245	6	420	294	2	140	98	2	140	98
17 COOLANOL PUMP							2	268	[illegible]	2	268	[illegible]
18 COOLANOL RESERVOIR							2	100	100	2	100	100
19 TEMP CONT VALVE	14	1120	1456	14	1120	1456	[illegible]	1040	1352	[illegible]	1040	1352
20 TEMP CONT VALVE BAR BIAS	12	1440	2016	12	1440	[illegible]	[illegible]	1440	2016	[illegible]	1440	2016
21 TEMP SENSOR	27	675	607.5	27	675	607.5	27	675	607.5	27	675	607.5
22 TEMP CONTROLLER	4	248	248	4	248	248	4	248	248	4	248	248
23 BLEED [illegible] VALVE							[illegible]	[illegible]	[illegible]	2	[illegible]	[illegible]
24 CHECK VALVE	1	13	13	1	13	13	2	26	26	2	26	26
25 COOLANOL TUBING & COUPLING				50	100	100	50	100	100	50	100	100
27 [illegible]	1	1	0.6	1	1	0.6	1	1	0.6	1	1	0.6
28 BLEED RAM AIR HT EXCH	2	6	14.4	2	6	14.4	[illegible]	[illegible]	21.6	[illegible]	9	21.6
29 [illegible] PRESSURE REG	2	232	278.4	2	232	278.4	[illegible]	348	417.6	[illegible]	348	417.6
30 [illegible]	10	710	426	10	710	426	16	1136	681.6	16	1136	681.6
31 [illegible] CONTROL	10	360	216	10	360	216	16	576	345.6	16	576	345.6
33 FAN SINGLE SPEED PNEU				2	142	170.4						
34 TURBINE COMP FAN ASSY	1	246	295.2									
35 [illegible] HEAT EXCH	1	3	7.2									
37 RAM AIR HEAT EXCH	10	30	60	10	30	60				[illegible]	2	6
38 TURBINE COMPRESSOR				1	150	270	1	150	240			
39 TURBINE COMP [illegible]							1	157	[illegible]			
40 [illegible] COMP ELECTRONICS							1	150	120			
41 [illegible] CONTROLLER							1	62	49.6			
42 COMP EXPANDER ASSY										1	250	350
43 [illegible]										1	25	25
44 [illegible]										1	100	80
45 [illegible] VALVE										1	25	25
46 WATER SEPARATOR				1	30	36						
48 [illegible]							2	52	31.2	2	52	31.2
49 DEHYDRATOR AIR							1	10	10	1	10	10
50 CAB [illegible]	1	116	92.8	1	116	92.8	1	116	92.8	1	116	92.8
51 CAB [illegible] VALVE	1	31	31	1	31	31	1	31	31	1	31	31
52 BLEED AIR [illegible]	10	10	12	10	10	12	10	10	12	10	10	12
53 AIR [illegible]	10	10	12	10	10	12	10	10	12	10	10	12
54 COCKPIT TEMP SELECTOR	1	8	4.8	1	8	4.8	1	8	4.8	1	8	4.8
TOTAL		5639	6084		5882	6184		[illegible]	[illegible]		[illegible]	[illegible]
MTBF		177HR			170HR			142HR			144HR	
MTTR			1.08			1.09			1.06			1.08

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APPENDIX C

LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

AEW	Airborne Early Warning
ASW	Anti Submarine Warfare
APU	Auxiliary Power Unit
CISE	Computerized Initial Sizing Estimate
D-Level	Depot Level Maintenance
ECS	Environmental Control System
GSE	Ground Support Equipment
ISEM 2A	Improved Standard Electronic Module, Size 2A
KW	Kilowatt
LCC	Life Cycle Costs
MLCCM	Modular Life Cycle Cost Models
MTBF	Mean Time Between Failures
MTBM	Mean Time Between Maintenance
MTTR	Mean Time to Repair
O-Level	Organizational (or aircraft) Level Maintenance
O&S	Operations and Support
RDT&E	Research, Development, Test, and Evaluation
R&M	Reliability and Maintainability
TOGW	Takeoff Gross Weight
V/STOL	Vertical and Short Takeoff and Landing
WRA	Weapons Replaceable Assembly